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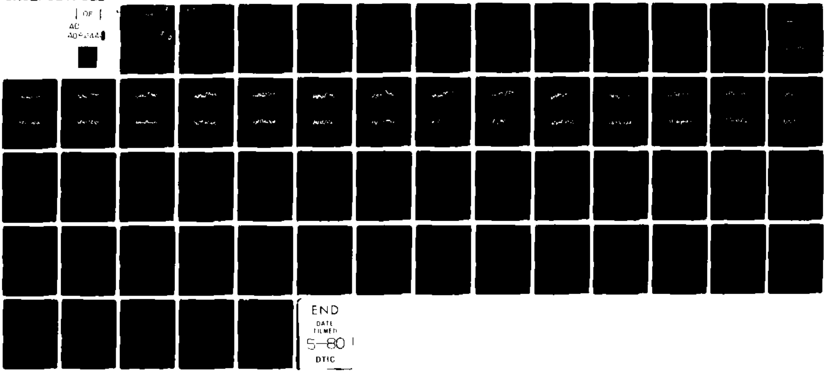

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DETECTION AND ESTIMATION OF SINGLE EVENT RELATED POTENTIALS

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The Performance of linear stepwise discriminant analysis and quadratic discriminant functions in classifying single event related brain potentials are compared. A frequent V and infrequent inverted V visual stimulus was employed and measurements were made with scalp electrodes at Pz, Cz, and Oz. Results are reported for using training data from one test to classify results of that test, to classify data from a test at a different time, and for classifying data from other subjects. Performance using the quadratic discriminant function was generally superior to that of the linear discriminant

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20. function. Single event classification accuracies greater than 90% were obtained when training and test data from the same experiment were used. Substantially poorer performance was obtained when data from one test was used to classify responses measured from a test conducted at a different time or using a different subject. Reasons for these discrepencies are discussed.

SUMMARY

This report describes research on two methods currently in use for the discrimination of evoked potentials. The two methods are linear stepwise discriminant analysis and Bayes or quadratic discrimination. The particular research discussed here is concerned with the 'V' inverted 'V' paradigm. A frequent event ('V') and an infrequent event (inverted 'V') were shown to two subjects on 4 separate experiments, each experiment consisting of approximately 550 total presentations. Comparison of the performance of the two classifiers when the same data was used to train and test revealed that the quadratic technique was more constant and out performed the linear technique in every case. Classification accuracy for these experiments was over 90%. When data from different days was used to train and test the classifier, the performance of both classifiers dropped to about 70%.

PREFACE

This research was performed by the School of Electrical Engineering, Purdue University, West Lafayette, Indiana under AF Contract No. F49620-79-C-0084 with Air Force Office of Scientific Research. Principal Co-investigators were Dr. Clare D. McGillem and Dr. Jorge I. Aunon. Program Manager was Dr. Alfred M. Fregly, Air Force Office of Scientific Research, Bolling Air Force Base, Washington, D.C. Technical Monitor was Lt. Col. Robert O'Donnell, Aerospace Medical Laboratory, Wright Patterson Air Force Base, Dayton, Ohio.

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INTRODUCTION

This report describes research on two methods currently in use for the discrimination of evoked potentials. The two methods are linear stepwise discriminant analysis and Bayes or quadratic discrimination. The particular research discussed here is concerned with the 'V' inverted 'V' paradigm. A frequent event ('V') and an infrequent event (inverted 'V') were shown to two subjects on four separate experiments, each experiment consisting of approximate by 550 total presentations. Comparison of the performance of the two classifiers when the same data was used to train and test revealed that the quadratic technique was more constant and outperformed the linear technique in every case. Classification accuracy for these experiments was over 90%. When data from different days was used to train and test the classifier, the performance of both classifiers dropped to about 70%.

BACKGROUND

Linear Stepwise Discriminant Analysis

The technique of linear stepwise discriminant analysis (LSDA) has been used by a number of researchers to analyze data obtained in studies of event related potentials (ERP) [Donchin, 1967, 1970, 1975; and Gardiner, 1969 a,b]. Typically data from two or more experiments are subjected to LSDA to ascertain if the recorded data are "different" and in what ways they differ the most. The technique is linear in nature; i.e., it assumes that a linear weighted sum of "features" will yield a discriminant score capable of accurately assessing the differences among the elements of the recorded data set.

The LSDA technique has been available in a packaged form since 1967 (Dixon, 1970) and has been known as BMD07M. Briefly the technique works as follows (Donchin, 1975):

Let the ERP following an event be denoted by a 1XN vector $A_{ki} = (a_{ki1}, a_{ki2}, \ldots, a_{kiN})$, where N is the number of time points, and k is a k-type stimulus presented for the i^{th} time. The parameter i ranges from 1 to P where P is the number of times event K occurred. For example: let the two conditions be a click at 45 dB above hearing threshold (k_1) and a click at 30 dB above hearing threshold (k_2). Each of the two stimuli is presented 100 times (P=100) and 80 points, 10^2 ms apart are recorded following each stimulus (N=80). These points are considered to be random variables.

A total of P 1XN vectors represents the set of data collected under any of the K conditions. These vectors may be arranged in a PXN matrix $\underline{A}_k$ where again k refers to a particular type of stimulus. When K=2, two such matrices exist, each comprising a set of P multivariate observations. These matrices are fed into a BMD07M program which then searches for a linear combination of these variables that would provide the maximum possible separation between the k groups. The linear combination has the effect of reducing each of the N-variate observations to one number thereby reducing the K N-variate observations to K univariate observations.

A measure of the separability between the two groups is given by the ratio of the quantities W and B is where W is the within-group variability and B the between-group variability. Each linear combination of the original variables produces a different B/W or F ratio and obviously one would like to find the one combination for which a minimum value of the F is obtained. This is by definition the combination of variables which will work best (in the LSDA sense) to separate the K experimental groups.

More rigorous definitions of B and W are as follows: W, the within - class scatter matrix for class k is given by

$$W = \sum_{k=1}^{K} W_k$$

where

$$W_k = \sum_{i=1}^{N_k} (a_{ik} - M_k)(a_{ik} - M_K)^T$$

a_{ik} = the i^{th} sample of class k

M_k = the mean of class k

N_k = the number of samples of class k

K = number of classes

B, the between - class scatter matrix is given by

$$B = \sum_{k=1}^{K} N_k (M_k - M_o)(M_k - M_o)^T$$

where M_o is the mean of all samples.

Once the variables have been selected which yield the lowest F it is possible to compute a classification matrix. Each of the input vectors of the original matrices A_k is classified into one of the K original classes according to the value of the discriminant function assigned to that vector. This in itself is a measure of the effectiveness of the procedure. Another measure of effectiveness computed by the program is the U statistic. The values of this statistic range from 0.0 to 1.0; the lower the number the greater the class separability.

The efficiency of the LSDA technique in the detection and comparison of ERPs was tested by Donchin in 1975 (Donchin, 1975). The procedure was first tested with data artificially generated. A data element or vector was assumed to be composed of the sum of a deterministic part and a random part. The deterministic part or signal is that portion of the brain potential related directly to the K-type event whereas the random part is that portion due to the ongoing EEG. This model may be represented mathematically as

$$a_{kit} = s_{kit} + n_{kit}$$

where s and n are the signal and noise respectively.

The signal model was composed of five damped sinusoids and the noise model was generated by a first order autoregressive process of the type

$$n_{kit} = b.n_{ki(t-1)} + Z_t$$

where b is the autoregressive constant for a particular simulated experiment and Z_t is the realization of a Gaussian random variable with a zero mean and constant variance.

Results from this study showed that for the signal and noise models assumed the LSDA technique detects "differences" in evoked potentials. A comment must be made, however, on the order of the autoregressive model utilized to describe the on-going EEG. On inspection of the data characteristics it appears that the first order model employed is totall, inadequate to represent the on-going EEG. A first order autoregressive process has as an autocorrelation function a decaying exponential which does not approximate the autocorrelation function of real on-going EEG. Other investigators have also found that high order models are needed to adequately describe the on-going EEG (Zetterberg, 1969; Kaveh, 1978). These results have also been confirmed in our laboratory at Purdue University. We are currently in the process of examining this discrepancy of model order in more detail.

Bayes or Quadratic Classifier

The Bayes classifier uses a decision rule based on a posteriori probabilities which is designed to give a minimum error or risk. If A is a data vector which can belong to any one of K classes with known a priori probabilities $P_1,\ldots,P_k$, the a posteriori probabilities can be calculated from the a priori probabilities and the conditional density functions p(A/1),...,p(A/K) where p(A/j) is the probability density functions of A given event j occurred. When the costs of all the different types of errors are the same, the Bayes decision rule to minimize the error becomes choosing the class which has the largest a posteriori probability or discriminant function:

$$h(A) = p(A/k)P_i \quad (k = 1,\ldots,K)$$

Thus the Bayes classifier requires either a knowledge or an estimate of the conditional probability density functions p(A/i),...,p(A/K). In the case these density functions are Gaussian with expected vectors M_k and covariance matrices C_k, the discriminant functions can be written as quadratic functions of A:

$$h(A) = \ln[p(A/k)P_k] \quad (k = 1,\ldots K)$$

$$h(A) = \ln P_k - \frac{1}{2} \ln|C_j| - \frac{1}{2} (A-M_k)^t C_k (A-M_k) \qquad (k = 1,\ldots,K)$$

When $C_1 = C_2 = C$, these quadratic functions reduce to linear functions of A:

$$h(A) = \ln P_k + M_k^T C^{-1} A - \frac{1}{2} M_k^T C^{-1} M_k \qquad (k = 1,\ldots,K)$$

when C = I the identity matrix, the Bayes classifier become the linear correlation classifier

$$h(A) = \ln P_k + M_k^T A - \frac{1}{2} M_k^t M_k \qquad (k = 1,\ldots,K)$$

Remembering that the Bayes classifier is optimum in the sense that it minimizes the error, one can see that the linear classifier will always give suboptimum performance unless p(A/1),...p(A/M) are Gaussian with equal covariance matrices. Thus, the linear classifier is an optimum classifier when the additive noise is Gaussian with the same covariance for the different classes; and the correlation classifier is an optimum classifier when, in addition, the additive noise is white.

The selection of the optimum set of features for this type of classification remains largely an unsolved problem. The technique utilized in this work is one called forward sequential feature selection (Fukunaga, 1972). Briefly, this technique first chooses the feature among all available features that gives the best discrimination using a 1-dimensional quadratic classifier. The next feature is chosen based on the best discrimination for a 2-dimensional classifier using the previously selected feature as one of the two. This step of adding a selected sample to the existing set continues until some predetermined number of features are chosen. This number depends on the total number of observations available to train the classifier.

Since there are three electrodes available each contributing 27 possible "features", it was decided to attempt classification utilizing all possible combination of electrodes, i.e., taking one electrode at a time; then all combinations of 2 electrodes and finally all combinations of three electrodes.

Results

The results presented first are for the two subjects, two experiments each. The same data used to train the classifier was also used to test the classifier.

EXPERIMENTAL DATA

The techniques just explained, LSDA and Bayes or quadratic classification have been tested utilizing a 'V' inverted 'V' paradigm. These tests were conducted in order to assess the appropriateness of the techniques in discriminating single evoked potentials.

The experiment involved two male graduate students as subjects, both workers in the laboratory, who were comfortably seated 1.3 meters in front of a visual display screen in a room with low ambient light level. These two subjects were tested twice, the second test being held approximately one month following the first. The letter 'V' or an inverted letter 'V', with measurements 2.8 cm X 2.1 cm was flashed on the screen for 0.75 seconds. The probability of a 'V' appearing was set at 0.9 and the probability of an inverted 'V' appearing set at 0.1. The interstimulus interval ranged between 3 and 5 seconds, the actual time being random with uniform distribution between these limits. Groups of 50 or 100 stimuli were presented with short periods of rest between groups, until a total of 550 responses was recorded. The experiment ran for about 2 hours. The brightness of the stimulus was adjusted to be as bright as possible without causing noticeable eye artifact in the eye channel.

Beckman silver-silver chloride electrodes were applied with conductive paste to sites Cz, Pz, and Oz as determined by the 10-20 system [Jasper, 1958] and were referenced to linked mastoids; forehead was used as ground. In addition, an eye channel was used to detect blink artifacts. Electrode impedence was measured at 30 Hz before and after the experiment and was held below 20 kΩ, typically measuring 3-4 kΩ. The signals were amplified by Grass 7P511 EEG amplifiers with low frequency cutoff of 0.1 Hz and high frequency cutoff of 100 Hz. Analog-to-digital conversion was accomplished at a rate of 250 samples per second with an A/D converter having 12 bits of precision.

Data included 750 msec of signal following the initial stimulation and 500 ms of data immediately preceeding the stimulus. All data was stored on digital magnetic tape as calibrated floating point microvolt values.

Analysis

All of the records stored on magnetic tape were searched for possible artifacts due to activity in the eye channel (due to blinks, etc.). The criterion for rejection was a change of amplitude greater than 50 μV within any 100 ms period. Since the probability of occurrence of an inverted 'V' (IV) was arbitrarily set at 0.1 (i.e. the infrequent event) a total of about 50 IV responses were available from the 550 total responses obtained. A corresponding group of fifty V responses was selected at random to make up the frequent event set.

The data was digitally filtered utilizing a low-pass filter with a cutoff frequency of 22.5 Hz. Every resulting fifth data point was used starting at 136 ms after stimulus and ending 656 ms following the stimulus. A total of 27 points per electrode site were thus obtained. Initially a visual inspection of the data was performed. Groups of 10 single ERP's following the stimulus were plotted superimposed. This was done for both sets of data. The data was plotted from approximately 140 ms to about 650 ms. A qualitative examination of the data revealed that a predominantly positive voltage existed in the area around 500 ms for the infrequent event. This result was found to be most prominent in the Pz electrode. Both of these results were anticipated and confirmed findings by other investigators (Donchin, 1975; 1978). Figures 1 through 16 show plots of the ERPs for these tests.

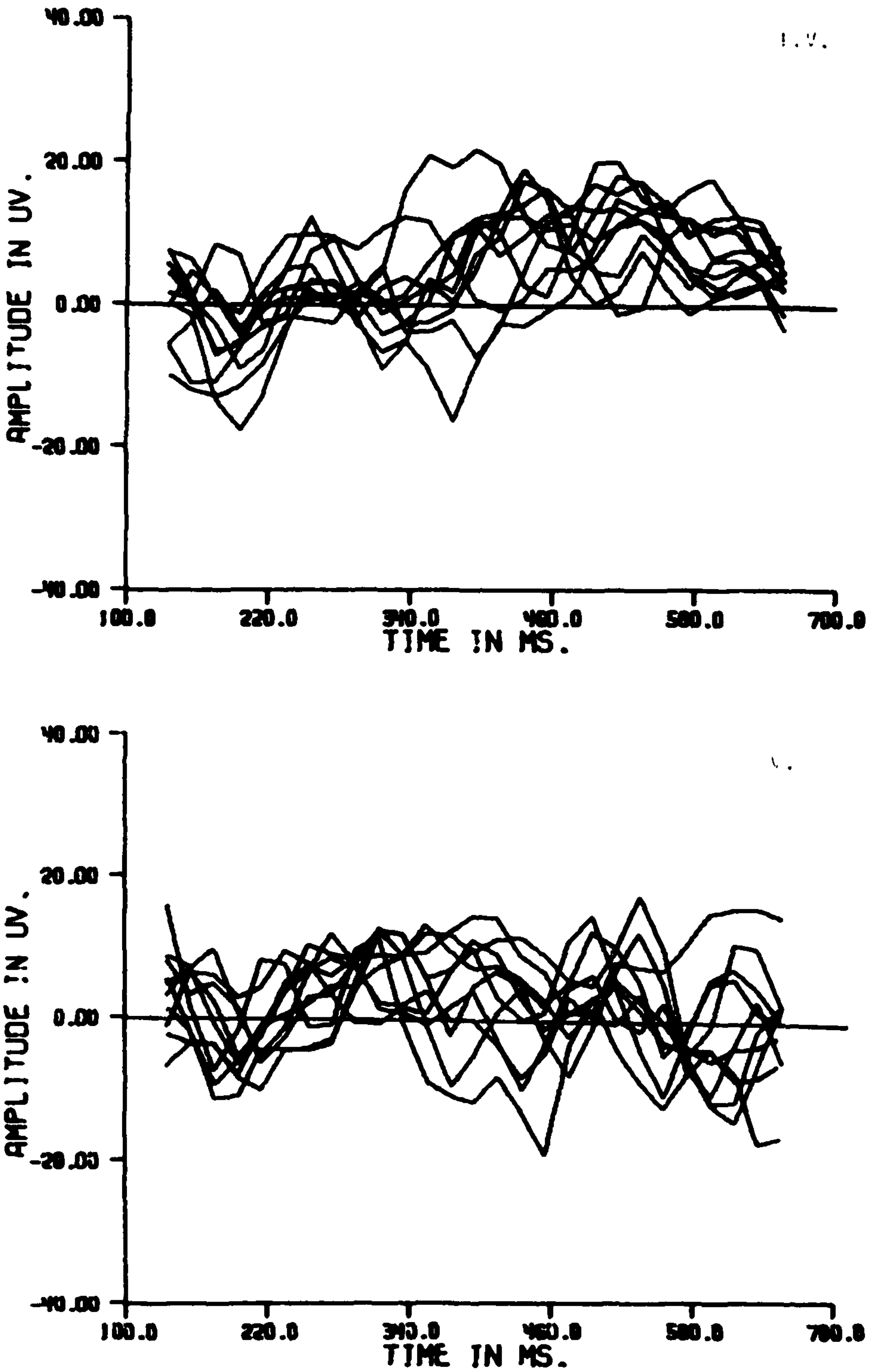


Figure 1. First subject, first test, Pz electrode - Tests 1-10.

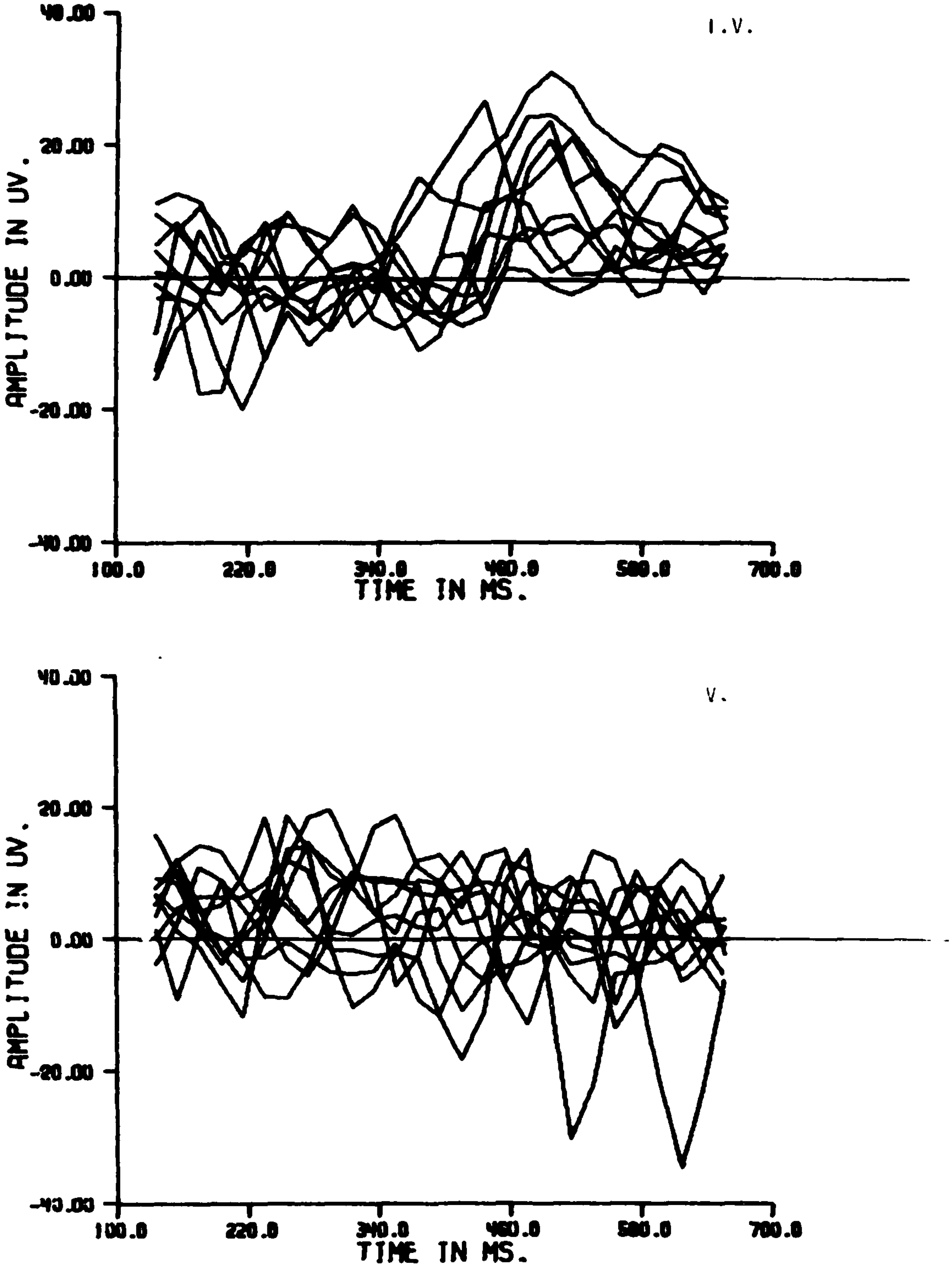


Figure 3. First subject, first test, Pz electrode - Tests 21-30.

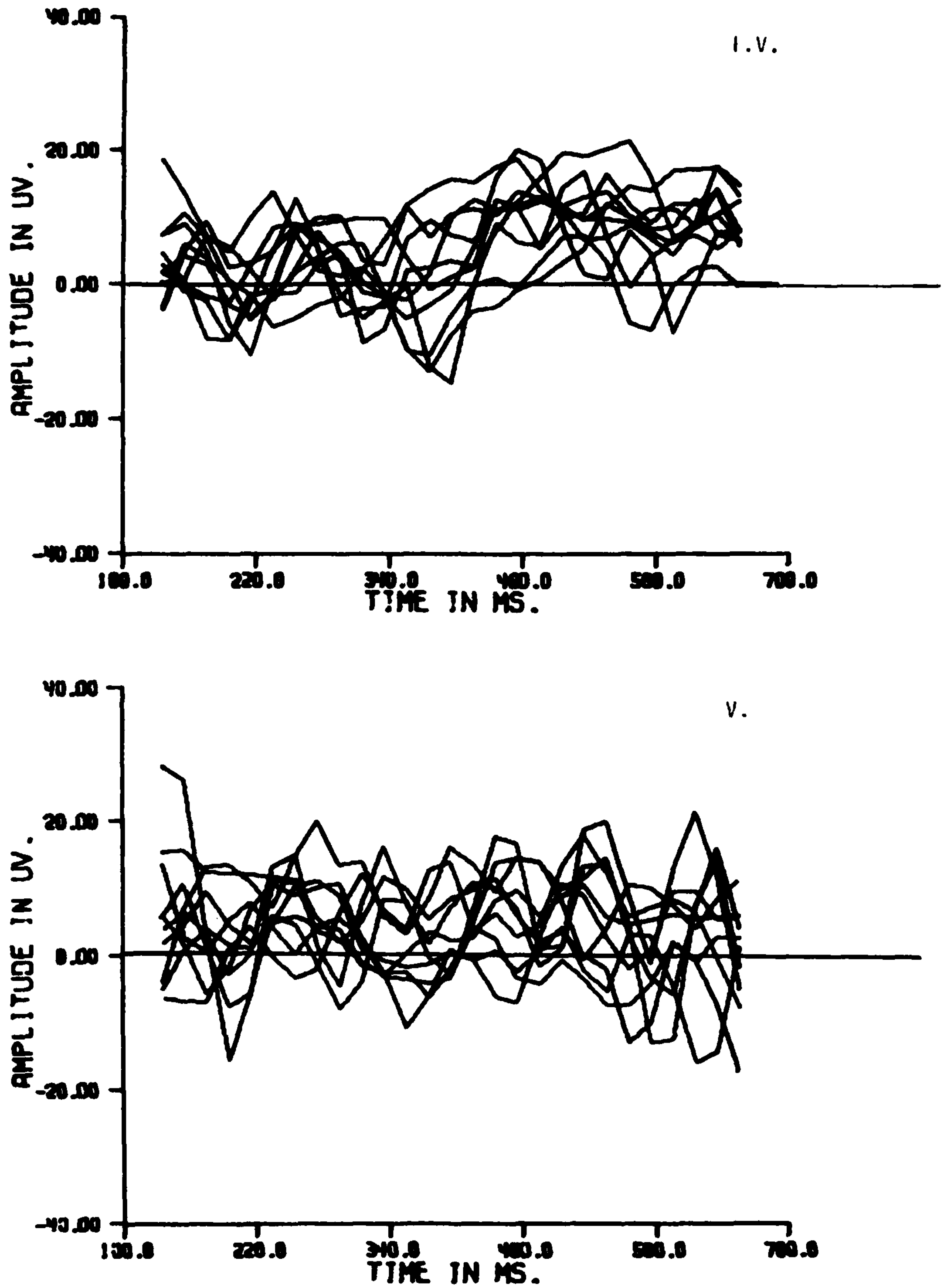


Figure 4. First subject, first test, Pz electrode - Tests 31-40.

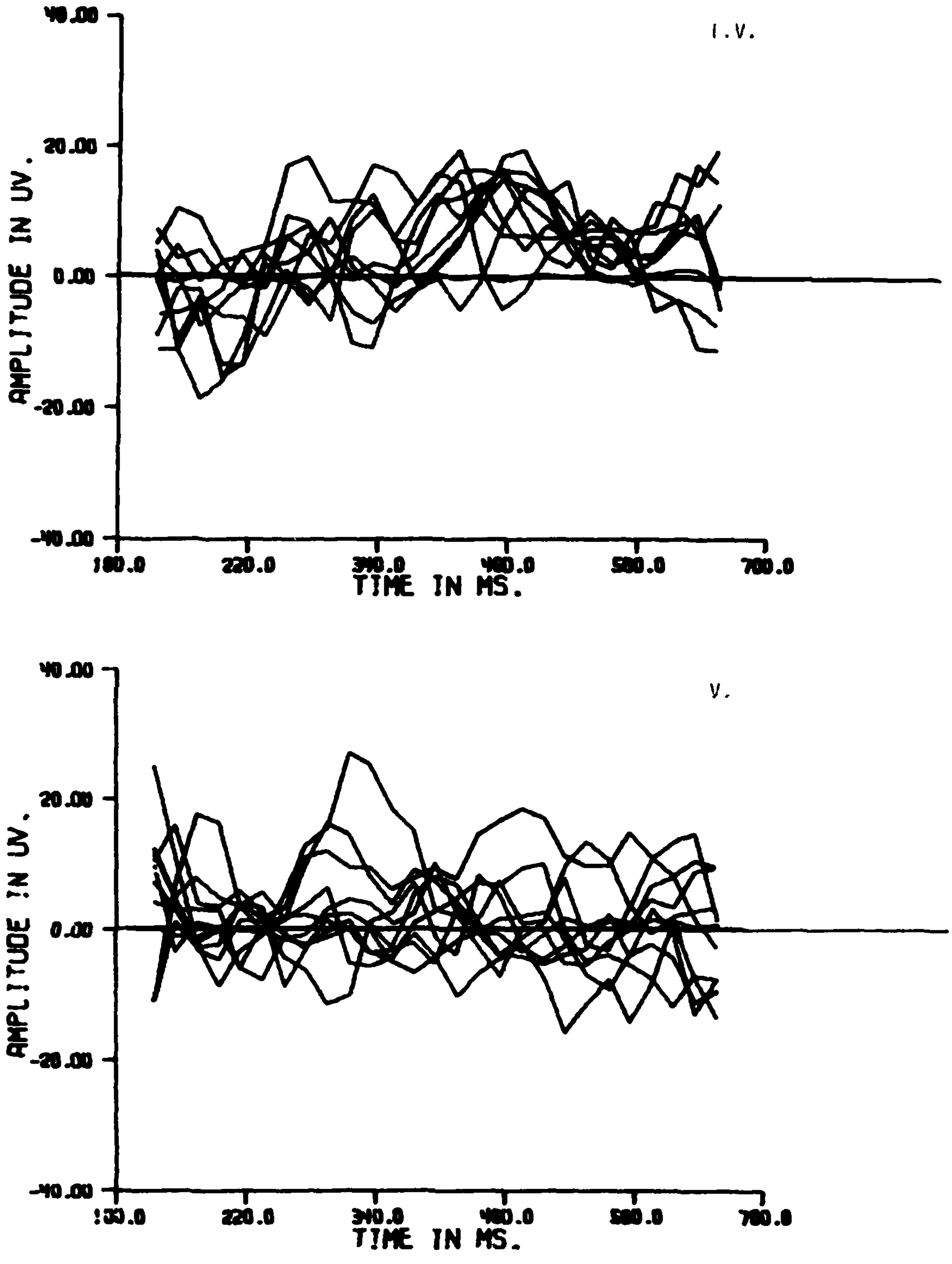
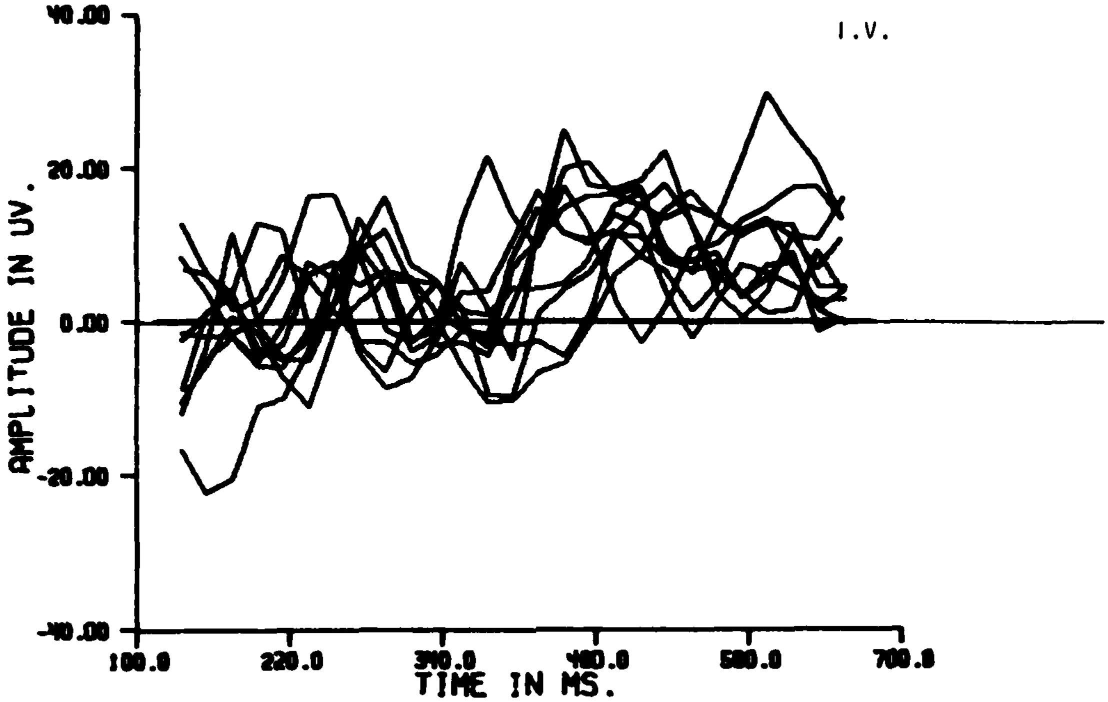


Figure 5. First subject, second test, Pz electrode - Tests 1-10.



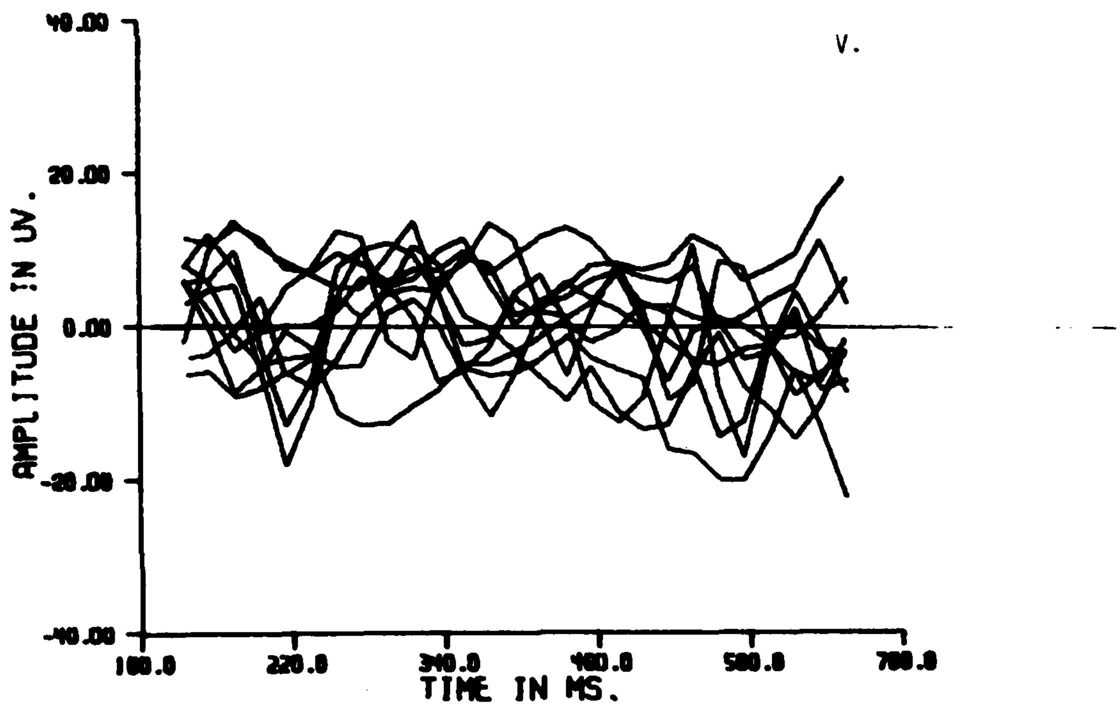
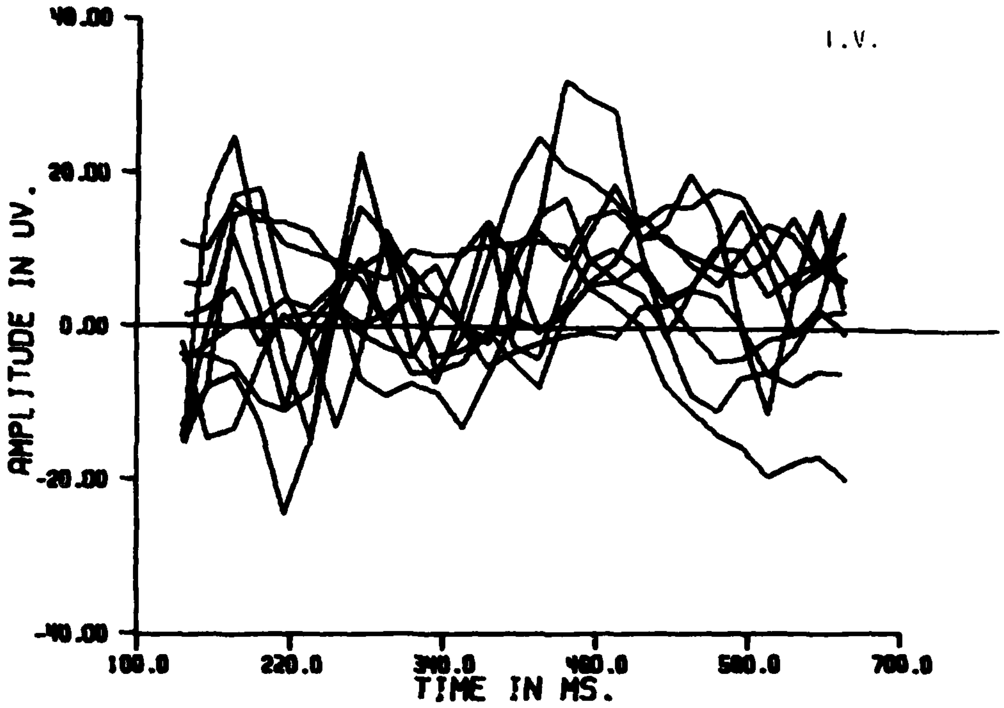


Figure 6. First subject, second test, Pz electrode - Tests 11-20.



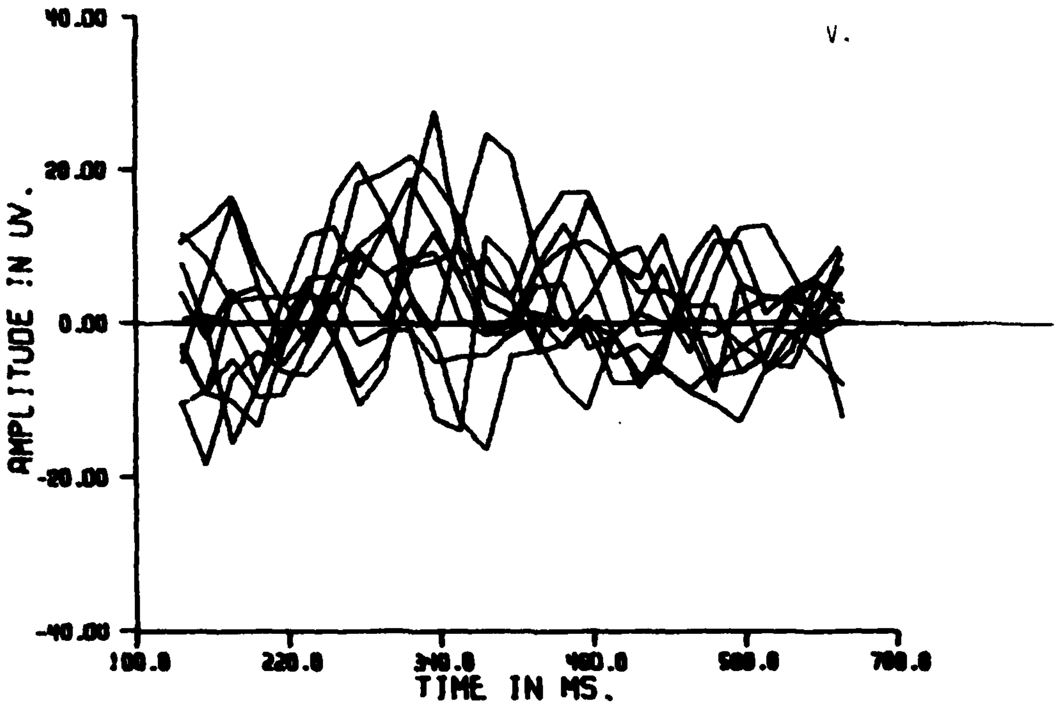


Figure 7. First subject, second test, Pz electrode - Tests 21-30.

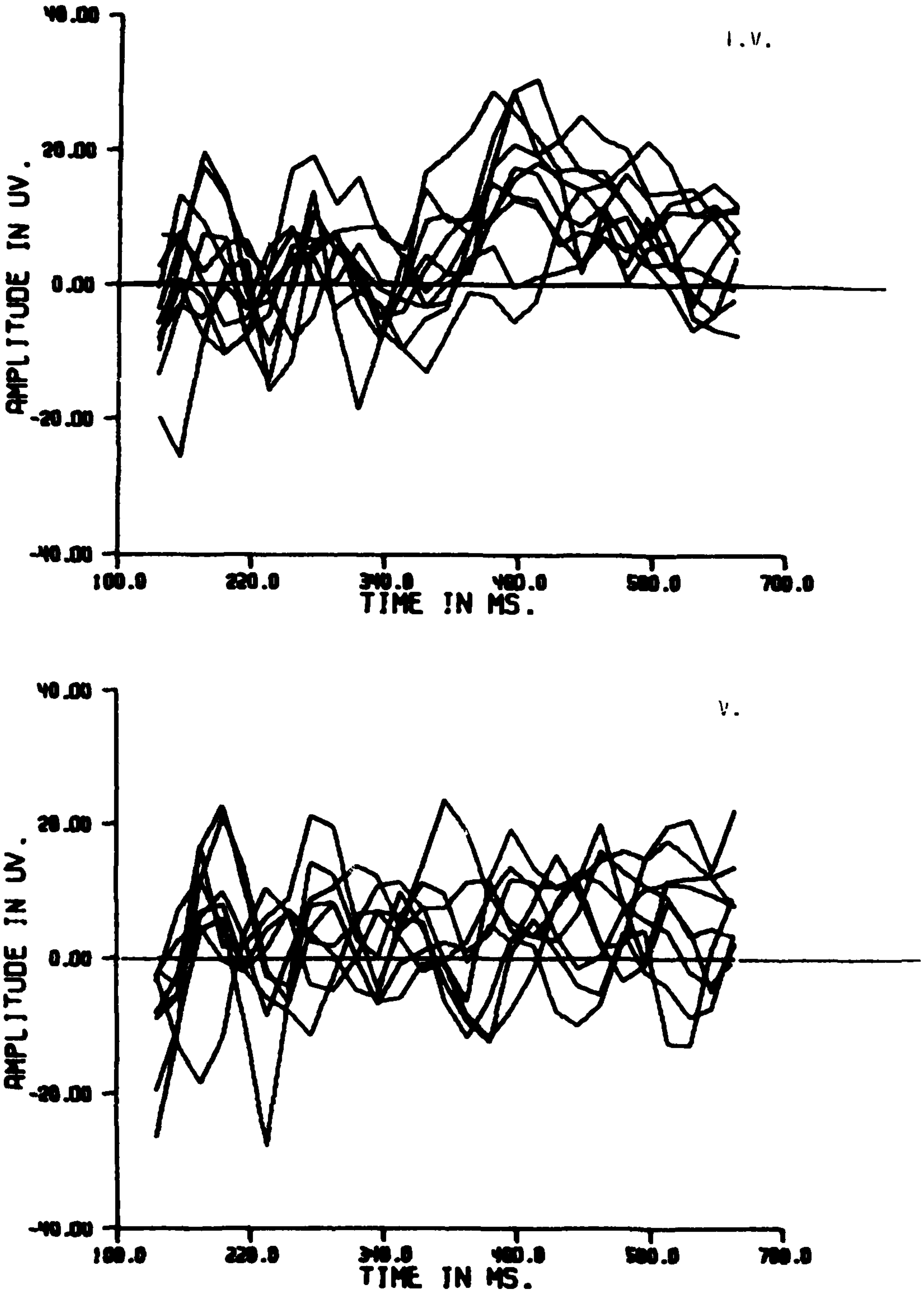
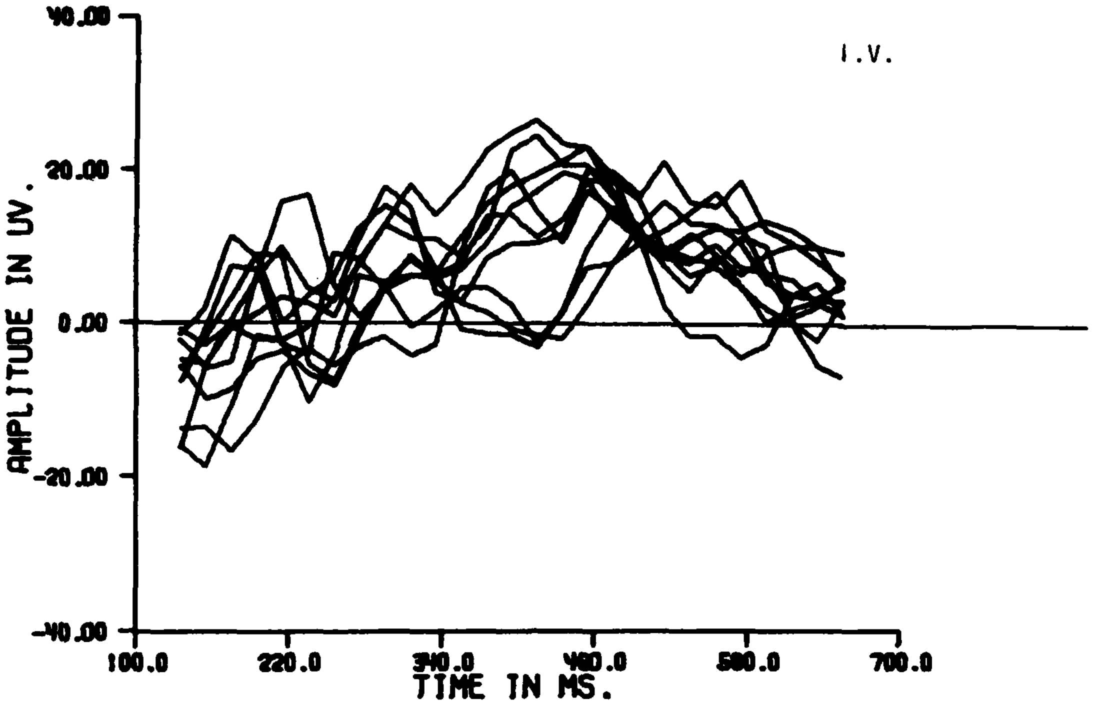


Figure 8. First subject, second test, Pz electrode - Tests 31-40.



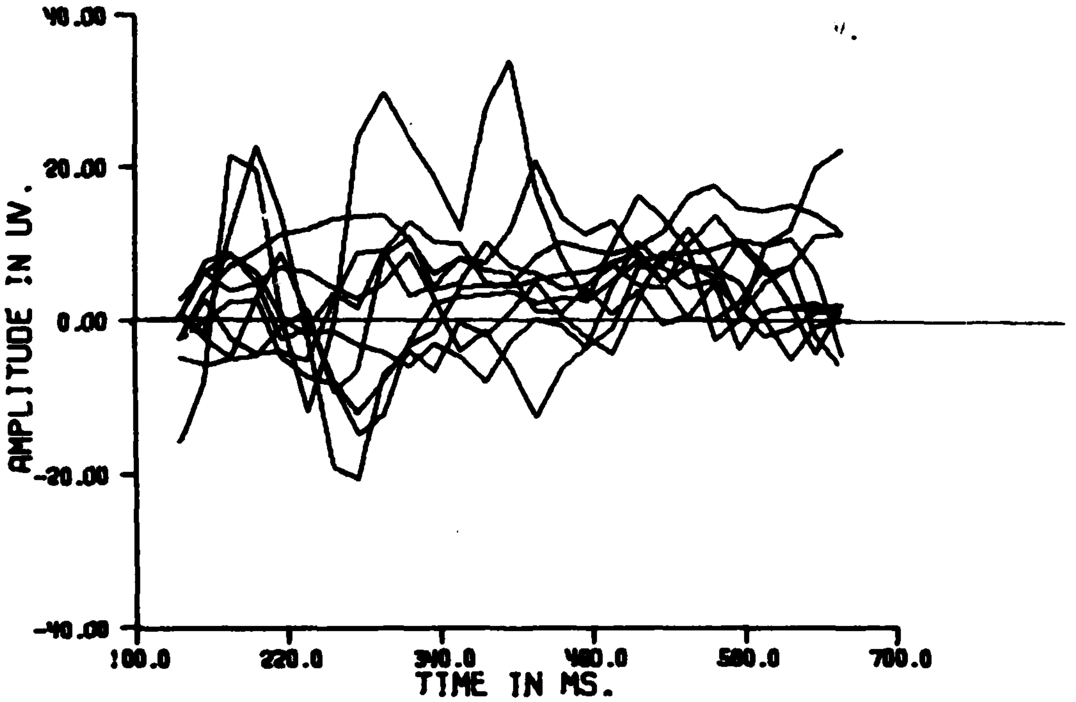


Figure 9. Second subject, first test, Pz electrode Tests 1-10.

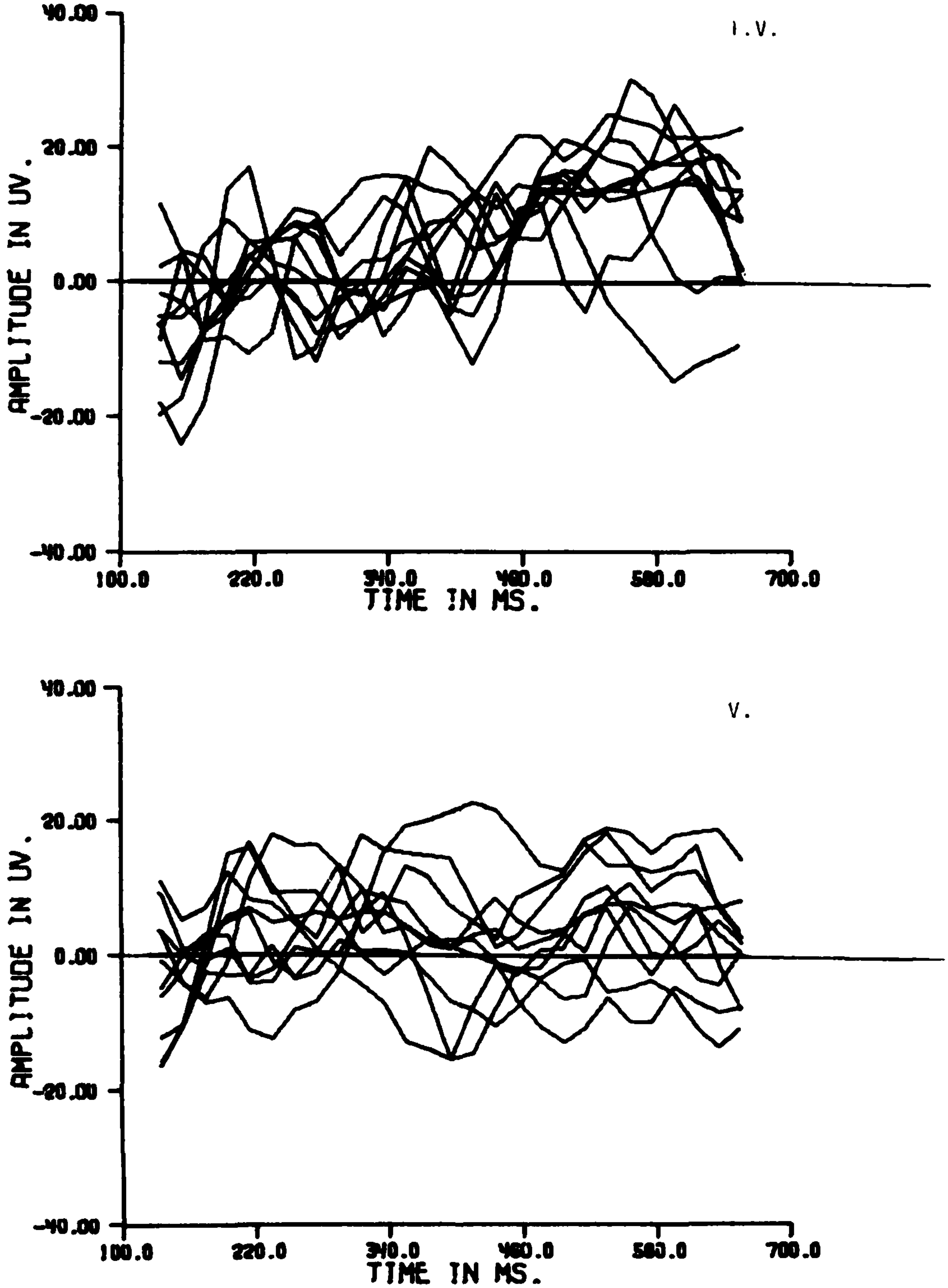


Figure 10. Second subject, first test, Pz electrode - Tests 11-20.

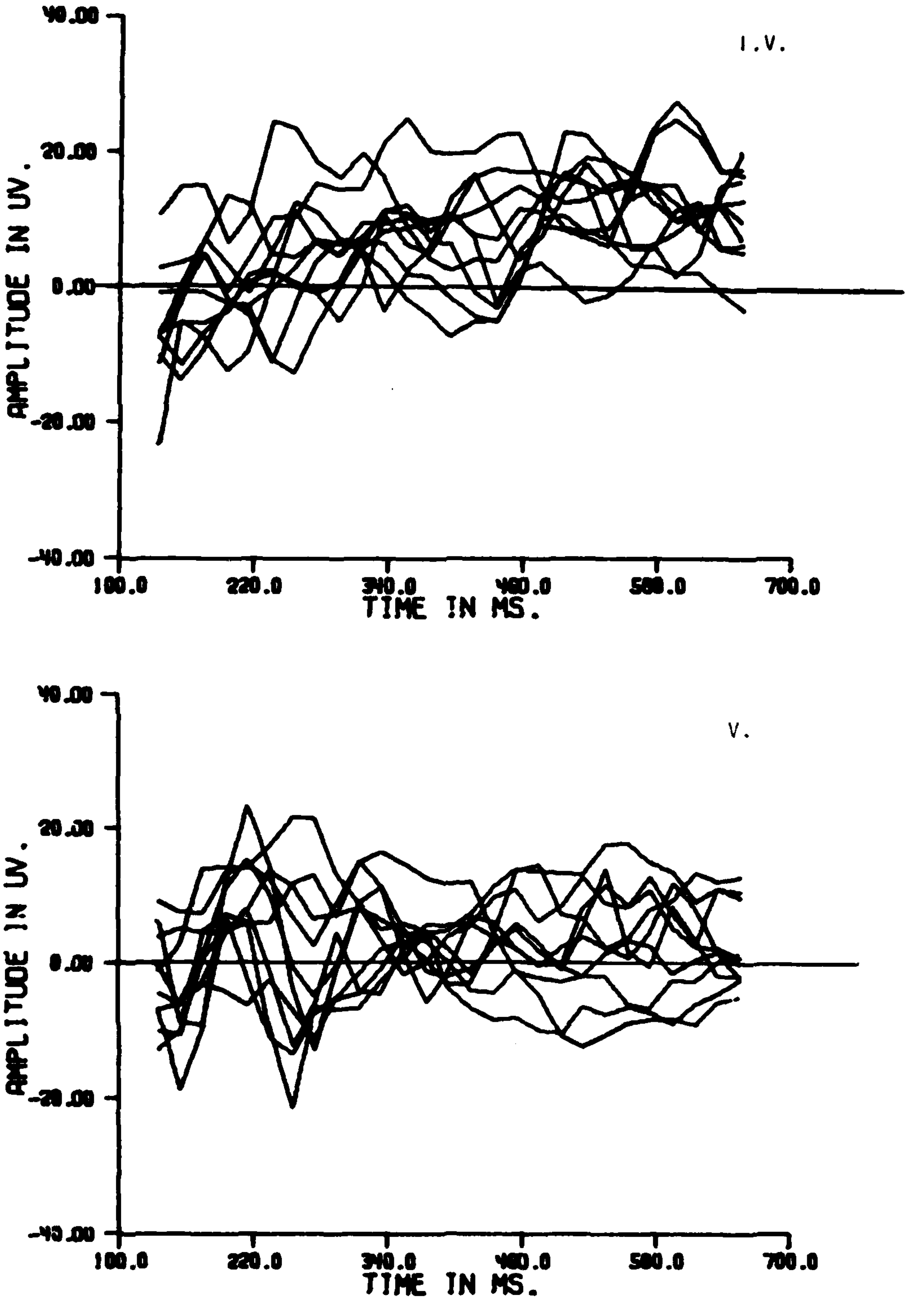
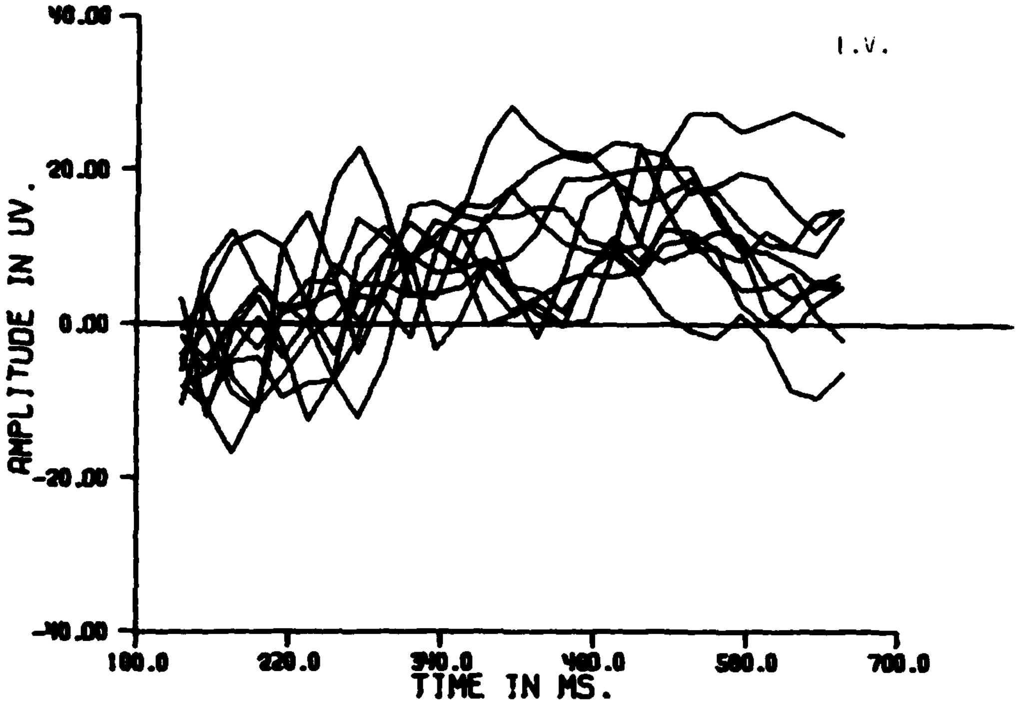


Figure 11. Second subject, first test, Pz electrode - Tests 21-30.



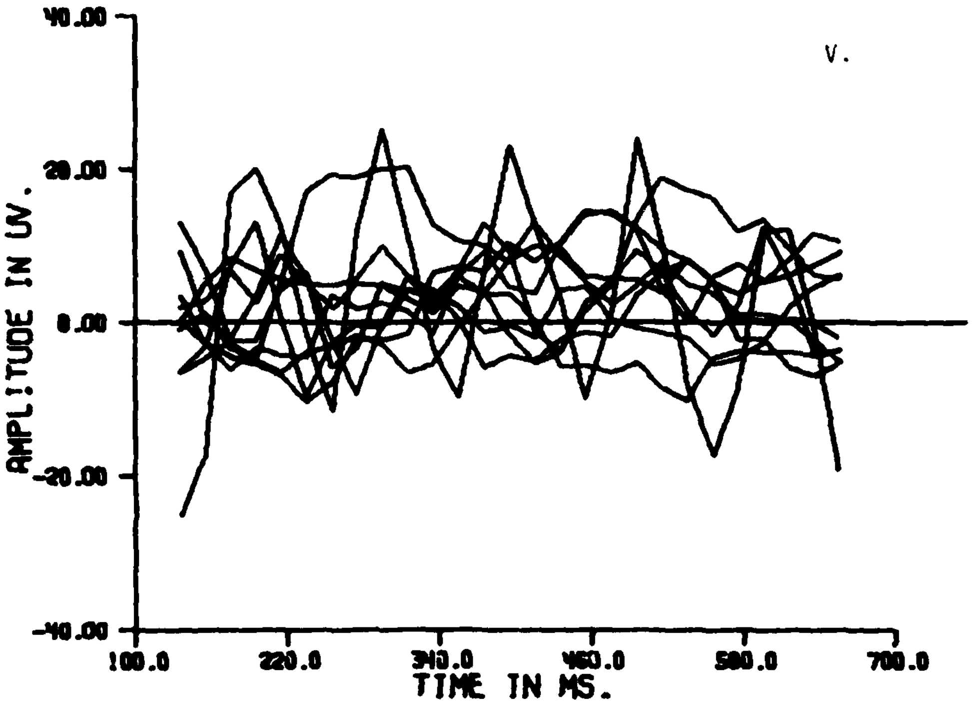
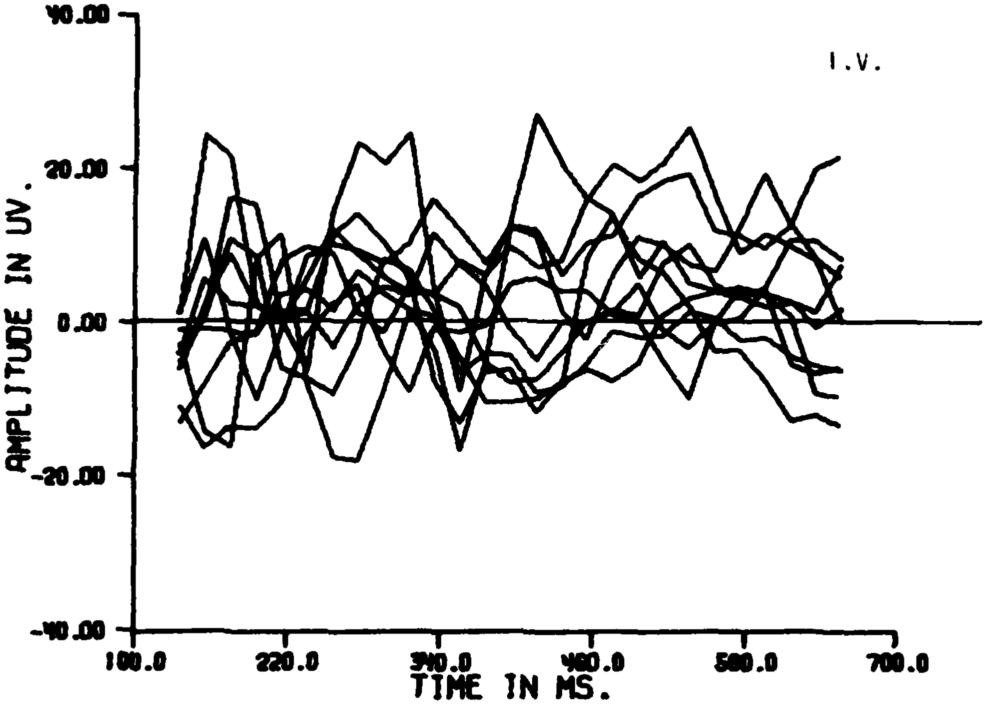


Figure 12. Second subject, first test, Pz electrode - Tests 31-40.



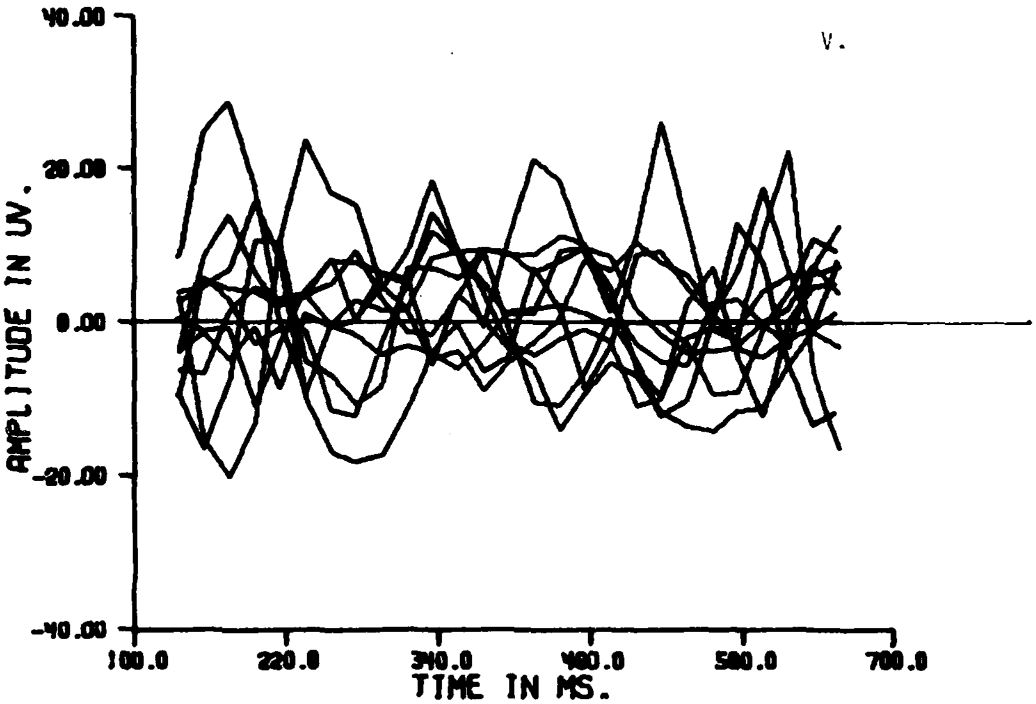


Figure 13. Second subject, second test, Pz electrode - Tests 1-10.

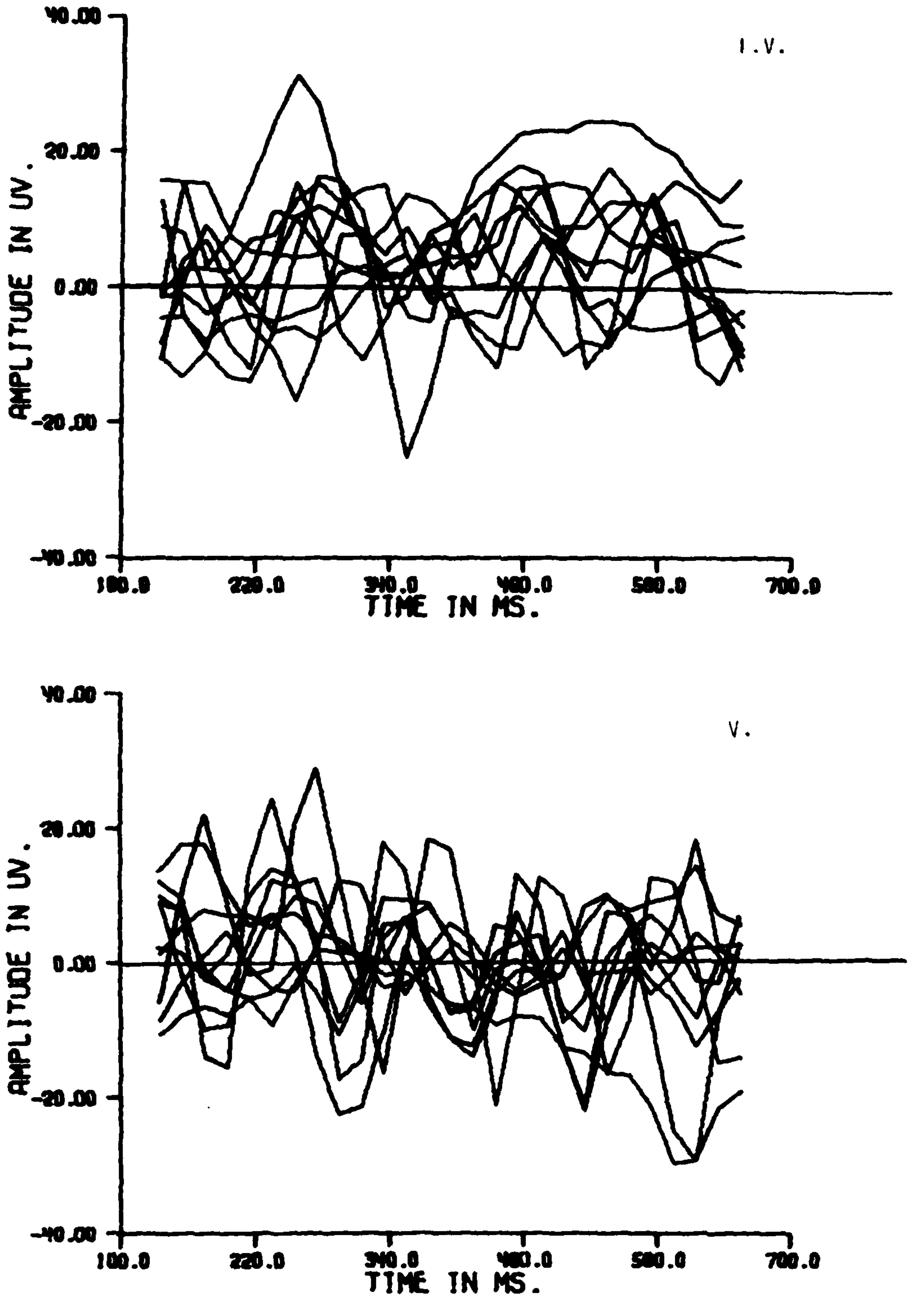
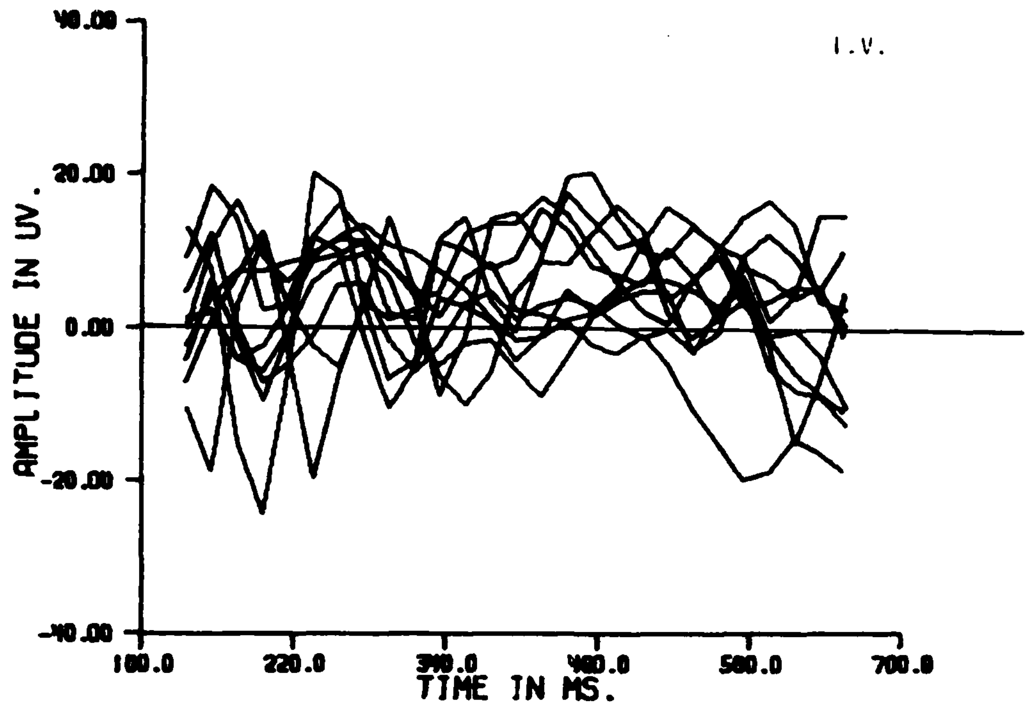


Figure 14. Second subject, second test, Pz electrode - Tests 11-20.



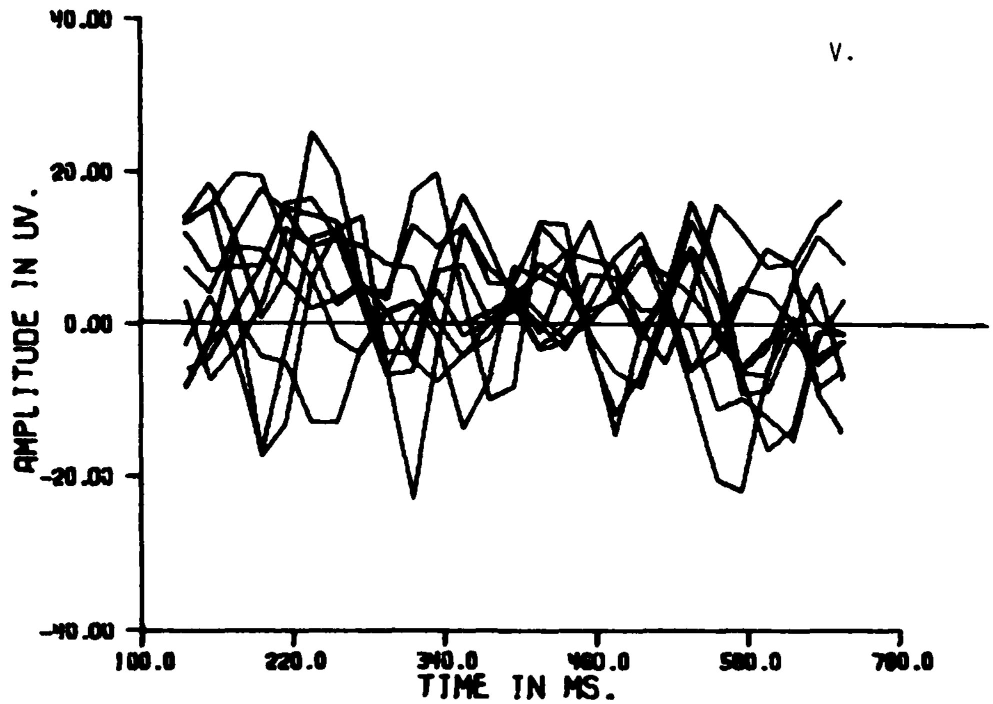


Figure 15. Second subject, second test, Fz electrode - Tests 21-30.

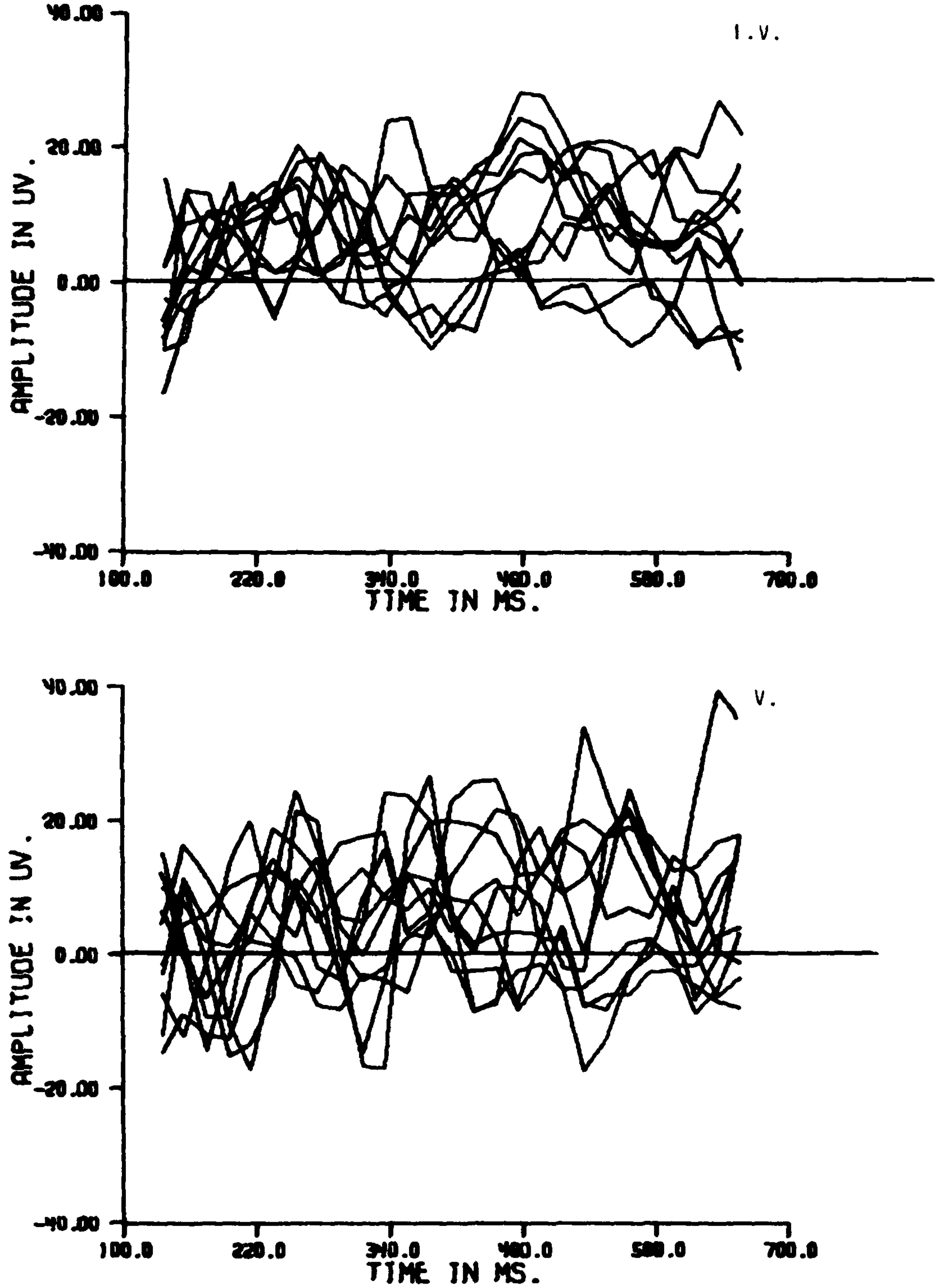


Figure 16. Second subject, second test, Fz electrode - Tests 31-40.

Figures 1 to 4 are for the first subject, first test and they show the first, second, third and fourth group of superimposed data for the Pz electrode. Only the Pz electrode is shown for brevity. The upper graph corresponds to the infrequent event IV and the lower graph to the frequent event V. A horizontal line through zero microvolts has been added as a reference. Figures 5 to 8 are for the first subject, second test. Figures 9 to 12 are for the second subject, first test. Figure 13 to 16 are for the second subject, second test. The predominance of an area of positivity in the infrequent event is clearly evident about 500 ms following stimulation. It is therefore anticipated that discrimination techniques will tend to use features from this area for discrimination purposes.

A comment on Features.

Typical ERP discrimination studies have utilized amplitude values at single latencies as the "features" to be used for discrimination (Donchin, 1978). There is, however, no reason not to try other data measures to supplement or replace the single latency values. Other types of physiological discrimination problems utilize very extensive descriptions of features or properties in addition to simple amplitude values. For the electrocardiogram, 157 features have been defined (Mucciardi, 1970) such as: amplitudes at selected time points, time integrals of selected waves, spatial maxima of selected waves, etc. The descriptions of some of these features could be readily applied to the cognitive ERP classification problem. It would even be logical to define experiment dependent features. For example, if a particular experimental paradigm is designed to elicit a P3 wave, such as the V, IV experiment, then some of the above feature definitions could be applied to the P3 wave such as energy, duration or moments about the centroid. It is worth noting, however, that with the existing feature definition (i.e. the amplitude at a single latency) very accurate classification results have been obtained (Sencaj, 1979; McGillem, 1979).

Data Results

The results obtained for the two subjects are quite extensive. This is due to all the possible permutations and combinations possible. For example, the data from the first subject, first test was used to train the classifier and the data from the first subject, second test was used to test the classifier performance to see if the results were stable over an extended time period. All of the tests were done using both the LSDA technique and the quadratic classifier technique and the quadratic classifier was employed using features from the LSDA procedure as well as features selected by the forward sequential feature selection procedure. In addition, all possible combinations of electrodes were used to ascertain the existence of a "best" electrode or electrode combination. All of the results are shown in Tables 1 to 56.

Each table identifies the subject and test number and the code next to the title identifies which data was used for training, which for classification and the data for which electrodes were available to the classifiers. The first five columns of each table give results for the LSDA technique. The first column identifies the feature order; the second column identifies the electrode site from which the feature was selected; the third column gives the feature latency; the fourth column is then classification accuracy obtained through the LSDA techniques and the fifth column is the accuracy obtained utilizing the quadratic classifier with the features defined by the LSDA technique. The next four columns give results for the FSFS technique. the sixth column is the feature order; the seventh column identifies the electrode site; the eighth column gives the feature latency and the ninth column is the classification accuracy obtained through the FSFS technique. The classification accuracy given at any row is the accuracy obtained the current and preceding features.

Table 1. First Subject, first experiment. Same data used to train and test. Oz electrode used.
Comments: LSDA and FSFS picked the same first 2 features; classification accuracy after 2 features 82% for LSDA and 86% for FSFS. First feature picked appears to be P300. After five features class. acc. for LSDA is 85% and for FSFS 90%.
Table 2. First Sub., first exp. Same data used to train and test. Pz electrode used
Comments: Same first feature picked by LSDA and FSFS. Class. acc. after 1 feature is 76%. P300 appears to have been picked by both techniques. After five features class. acc. for LSCA is 86% and for FSFS is 94%.
Table 3. First Subj., first exp. Same data used to train and test. Cz electrode used.
Comments: P300 appears to have been picked by both techniques. Initial class. acc. after one feature for either technique is about 73%. Afte five features, class. acc. for LSCA is 83% and for FSFS is 89%.
Table 4. First subject, first exp. Same data used to train and test. Oz and Pz electrodes used.
Comments: Note that the data from electrodes 2 are now available for the two techniques to pick features from. The most conspicuous result is that the LSDA technique picked four out of the five features from the Pz electrode achieving 86% class. acc. after five features. On the other hand, the FSFS technique picked three out of the five features from the Oz electrode achieving 94% class. acc. after five features.
Table 5. First subject, first exp. Same data used to train and test. Oz and Cz electrodes used.
Comments: After five features the LSDA class. acc. is 90% and the FSFS class. acc. is 94%.
Table 6. First subject, first exp. Same data used to train and test. Pz and Cz electrodes used.
Comments: After five features the LSDA class acc. is 85% and the FSFS class. acc. is 94%.
Table 7. First subject, first exp. Same data used to train and test. Oz, Pz and Cz electrodes used.
Comments: Note that the data from all electrodes is now available to both techniques. After five features, the LSDA class. acc. is 89% and the FSFS class. acc. is 94%
General comments on Tables 1 to 7.

The amplitude of the area about 575 ms was consistently picked first as a feature by either technique; this is probably the location of the "cognitive" wave or P300. Classification accuracy after 5 features was as follows:

Table 1. Classification accuracies obtained for subject 1, test 1 (TR1/CL1; Oz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. Accuracy LSDA	Class. Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	576	75%	79%	1	Oz	576	79%
2	Oz	196	83%	86%	2	Oz	196	86%
3	Oz	276	84%	81%	3	Oz	176	88%
4	Oz	476	85%	84%	4	Oz	216	86%
5	Oz	336	85%	84%	5	Oz	496	90%

Table 2. Classification accuracies obtained for subject 1, test 1 (TR1/CL1; Pz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. Accuracy LSDA	Class. Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	576	76%	74%	1	Pz	656	76%
2	Pz	296	84%	83%	2	Pz	576	81%
3	Pz	476	83%	81%	3	Pz	276	88%
4	Pz	156	84%	84%	4	Pz	436	93%
5	Pz	376	86%	84%	5	Pz	156	94%

Table 3. Classification accuracies obtained for subject 1, test 1 (TR1/CL1; Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. Accuracy LSDA	Class. Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Cz	576	73%	73%	1	Cz	296	74%
2	Cz	296	80%	80%	2	Cz	556	84%
3	Cz	476	83%	81%	3	Cz	156	86%
4	Cz	376	84%	85%	4	Cz	396	88%
5	Cz	656	83%	86%	5	Cz	276	89%

Table 4. Classification accuracies obtained for subject 2, test 1 (TR1/CL1; Oz,Pz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. Accuracy LSDA	Class. Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	576	76%	74%	1	Oz	576	79%
2	Oz	196	84%	84%	2	Oz	196	86%
3	Pz	476	84%	85%	3	Pz	656	91%
4	Pz	296	84%	84%	4	Oz	216	91%
5	Pz	216	86%	85%	5	Pz	296	94%

Table 5. Classification accuracies obtained for subject 2, test 1 (TR1/CL1; Oz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. Accuracy LSDA	Class. Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Cz	576	73%	73%	1	Oz	576	79%
2	Oz	196	85%	85%	2	Oz	196	86%
3	Cz	296	85%	84%	3	Cz	276	90%
4	Cz	476	86%	84%	4	Cz	596	94%
5	Cz	196	90%	86%	5	Oz	256	94%

Table 6. Classification accuracies obtained for subject 1, test 1 (TR1/CL1; Pz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. Accuracy LSDA	Class. Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	576	76%	74%	1	Pz	656	76%
2	Cz	296	81%	84%	2	Pz	576	81%
3	Cz	476	81%	85%	3	Cz	276	90%
4	Pz	176	85%	85%	4	Cz	416	93%
5	Cz	176	85%	86%	5	Pz	176	94%

Table 7. Classification accuracies obtained for subject 2, test 1 (TR1/CL1; Oz,Pz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. Accuracy LSDA	ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	576	76%	74%	1	Oz	576	79%
2	Oz	196	84%	84%	2	Oz	196	86%
3	Cz	296	85%	86%	3	Pz	656	91%
4	Cz	196	88%	88%	4	Oz	216	91%
5	Pz	476	88%	89%	5	Pz	296	94%

Table 8. Classification accuracies obtained for subject 2, test 1 (TR1/CL1; Oz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. Accuracy LSDA	ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	476	79%	79%	1	Oz	476	79%
2	Oz	196	81%	82%	2	Oz	136	82%
3	Oz	136	86%	86%	3	Oz	596	88%
4	Oz	236	84%	86%	4	Oz	616	89%
5	Oz	216	81%	85%	5	Oz	256	91%

Table 9. Classification accuracies obtained for subject 2, test 1 (TR1/CL1; Pz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. Accuracy LSDA	ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	476	81%	81%	1	Pz	476	81%
2	Pz	516	83%	83%	2	Pz	136	85%
3	Pz	276	84%	85%	3	Pz	376	90%
4	Pz	196	88%	88%	4	Pz	256	89%
5	Pz	136	91%	90%	5	Pz	156	91%

Electrode(s)	LSDA(%)	FSFS(%)
Oz	85	90
Pz	86	94
Cz	83	89
Oz,Pz	86	94
Oz,Cz	90	94
Pz,Cz	85	94
Oz,Pz,Cz	88	94

For this subject, first experiment, the FSFS classification technique out-performed the LSDA technique in all cases. Least classification accuracy was obtained for features from the Cz electrode.

Table 8. Second subject, first experiment. Same data used to train and test. Oz electrode used.

Comments: LSDA and FSFS picked the same first feature which appears to be P300. After five features class. acc. for LSDA is 81% and for FSFS 91%. Note that after 3 features LSDA acc. was 86% thereafter decreasing to 81%.

Table 9. Second subject, first experiment. Same data used to train and test. Pz electrode used.

Comments: First feature at 476 ms. picked by both techniques. After five features class acc. for LSDA is 91% and for FSFS 91%.

Table 10. Second subject, first experiment. Same data used to train and test. Cz electrode used.

Comments: First feature picked by both techniques are practically the same. After five features class. acc. for LSDA is 71% and for FSFS is 89%.

Table 11. Second subject, first experiment. Same data used to train and test. Oz and Pz electrodes used.

Comments: First feature picked by both technique is from different electrodes but at the same latency. After five features class. acc. for LSDA is 85% and for FSFS is 90%.

Table 12. Second subject, first experiment. Same data used to train and test. Oz and Cz electrodes used.

Comments: Same first feature picked by both techniques. After five features class. acc. for LSDA is 90% and for FSFS is 90%.

Table 13. Second subject, first experiment. Same data used to train and test. Pz and Cz electrodes used.

Comments: Same first feature picked by both techniques. After five features class. acc. for LSDA is 88% and for FSFS is 89%.

Table 14. Second subject, first experiment. Same data used to train and test. Oz, Pz and Cz electrodes used.

Comments: First features picked are from different electrodes but at the same latency. After five features class. acc. for LSDA is 92% and for FSFS is 93%.

General comments on Tables 8 to 14.

The amplitude of the area about 475 ms was consistently picked first as a feature by each technique; as with the first subject this is probably the location of the "cognitive" wave or P300. This wave had a latency of 575 ms for the first subject. Classification accuracy after 5 features was as follows:

Table 10. Classification accuracies obtained for subject 2, test 1 (TR1/CL1; Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Cz	476	68%	68%	1	Cz	516	69%
2	Cz	196	70%	71%	2	Cz	256	75%
3	Cz	256	73%	71%	3	Cz	176	80%
4	Cz	576	75%	79%	4	Cz	376	85%
5	Cz	136	71%	79%	5	Cz	596	89%

Table 11. Classification accuracies obtained for subject 2, test 1 (TR1/CL1; Oz,Pz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	476	79%	79%	1	Pz	476	81%
2	Oz	196	84%	83%	2	Oz	536	86%
3	Pz	256	81%	84%	3	Oz	216	88%
4	Oz	156	84%	88%	4	Pz	316	90%
5	Pz	476	85%	89%	5	Oz	316	90%

Table 12. Classification accuracies obtained for subject 2, test 1 (TR1/CL1; Oz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	476	79%	78%	1	Oz	476	79%
2	Oz	196	84%	82%	2	Cz	576	85%
3	Cz	256	81%	81%	3	Oz	176	86%
4	Cz	376	90%	90%	4	Oz	136	86%
5	Cz	136	90%	90%	5	Oz	236	90%

Table 13. Classification accuracies obtained for subject 2, test 1 (TR1/CL1; Pz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	476	83%	81%	1	Pz	476	81%
2	Pz	196	83%	83%	2	Cz	216	86%
3	Cz	436	86%	84%	3	Pz	336	89%
4	Cz	276	86%	86%	4	Pz	216	90%
5	Cz	376	88%	90%	5	Pz	156	89%

Table 14. Classification accuracies obtained for subject 2, test 1 (TR1/CL1; Oz,Pz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	476	79%	79%	1	Pz	476	81%
2	Oz	196	83%	83%	2	Oz	536	86%
3	Cz	256	81%	81%	3	Cz	376	89%
4	Cz	376	90%	90%	4	Oz	196	90%
5	Pz	476	92%	89%	5	Cz	516	93%

Table 15. Classification accuracies obtained for subject 1, test 2 (TR1/CL1; Oz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	496	64%	65%	1	Oz	496	66%
2	Oz	656	68%	69%	2	Oz	536	73%
3	Oz	316	71%	71%	3	Oz	336	78%
4	Oz	516	78%	79%	4	Oz	156	78%
5	Oz	136	70%	74%	5	Oz	596	84%

Electrode(s)	LSDA(%)	FSFS(%)
Oz	81	91
Pz	91	91
Cz	71	89
Oz,Pz	85	90
Oz,Cz	90	90
Pz,Cz	88	89
Oz,Pz,Cz	92	93

For this subject, first experiment, the performance of the LSDA technique was equal to or less than the performance of the FSFS technique. Classification accuracy obtained through the FSFS technique was very constant ranging from 89% to 93%. On the other hand, the accuracy obtained with the LSDA technique ranged widely between a low of 71% and a high of 92%. In no case did the accuracy obtained under the LSDA technique outperformed the accuracy obtained under the FSFS technique. As mentioned earlier the FSFS technique yielded very consistent results.

Table 15. First subject, second experiment. Same data used to train and test. Oz electrode used.

Comments: Same first feature picked by both techniques. After five features, class. acc. for LSDA is 70% and for FSFS is 84%. Note that after four features class. acc. for both techniques was the same (78%) and with the fifth feature, LSDA dropped to 70% and FSFS increased to 84%.

Table 16. First subject, second experiment. Same data used to train and test. Pz electrode used.

Comments: Same first feature picked by both techniques. After five features, class. acc. for LSDA is 82% and for FSFS is 91%.

Table 17. First subject, second experiment. Same data used to train and test. Cz electrode used.

Comments: LSDA technique picked as it's first feature the amplitude at 496 ms, whereas FSFS picked the amplitude at 476 ms. These are adjacent points so they should be essentially considered to be the same feature. After five features, class. acc. for LSDA is 80% and for FSFS is 89%.

Table 18. First subject, second experiment. Same data used to train and test. Oz and Pz electrodes used.

Comments: Same first feature picked by both techniques. After five features, class. acc. for LSDA is 86% and for FSFS is 91%.

Table 19. First subject, second experiment. Same data used to train and test. Oz and Cz electrodes used.

Comments: First feature picked by each technique is the same. Note that under FSFS, feature 46 (at 496 ms) ranked equally with feature 45 (at 476 ms). After five features, class. acc. for LSDA is 82% and for FSFS is 90%.

Table 20. First subject, second experiment. Same data used to train and test. Pz and Cz electrodes used.

Comments: First feature picked by each technique is the same. After five features, class. acc. for LSDA is 82% and for FSFS is 91%.

Table 21. First subject, second experiment. Same data used to train and test. Oz, Pz and Cz electrodes used.

Comments: First feature picked by each technique is the same. After five features, class. acc. for LSDA is 86% and for FSFS is 91%.

General comments on Tables 15 to 21.

Table 16. Classification accuracies obtained for subject 1, test 2 (TR1/CL1; Pz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	496	76%	76%	1	Pz	496	76%
2	Pz	316	78%	78%	2	Pz	136	80%
3	Pz	416	83%	84%	3	Pz	376	84%
4	Pz	376	81%	83%	4	Pz	456	89%
5	Pz	556	83%	84%	5	Pz	656	91%

Table 17. Classification accuracies obtained for subject 1, test 2 (TR1/CL1; Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Cz	496	74%	74%	1	Cz	476	74%
2	Cz	416	75%	76%	2	Cz	356	81%
3	Cz	376	75%	76%	3	Cz	536	85%
4	Cz	316	78%	79%	4	Cz	616	88%
5	Cz	636	80%	83%	5	Cz	456	89%

Table 18. Classification accuracies obtained for subject 1, test 2 (TR1/CL1; Oz,Pz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	496	76%	76%	1	Pz	496	76%
2	Oz	656	78%	78%	2	Pz	136	80%
3	Pz	556	81%	74%	3	Pz	376	84%
4	Oz	316	84%	79%	4	Pz	456	89%
5	Oz	156	86%	81%	5	Oz	476	91%

Table 19. Classification accuracies obtained for subject 1, test 2 (TR1/CL1; Oz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Cz	496	74%	74%	1	Cz	476	74%
2	Oz	656	74%	75%	2	Cz	356	81%
3	Oz	436	79%	79%	3	Cz	536	85%
4	Oz	316	81%	83%	4	Oz	156	88%
5	Cz	636	83%	83%	5	Oz	476	90%

Table 20. Classification accuracies obtained for subject 1, test 2 (TR1/CL1; Pz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	496	76%	76%	1	Pz	496	76%
2	Pz	316	78%	78%	2	Pz	136	80%
3	Cz	416	79%	80%	3	Pz	376	84%
4	Cz	376	81%	83%	4	Pz	456	89%
5	Pz	576	83%	83%	5	Pz	656	91%

Table 21. Classification accuracies obtained for subject 1, test 2 (TR1/CL1; Oz,Pz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	496	76%	76%	1	Pz	496	76%
2	Oz	656	81%	78%	2	Pz	136	80%
3	Pz	556	81%	74%	3	Pz	376	84%
4	Oz	316	84%	81%	4	Pz	456	89%
5	Cz	416	86%	88%	5	Oz	476	91%

The amplitude of the area about 496 ms was consistently picked first as a feature by each technique; this is probably the location of the "cognitive" wave or P300. Classification accuracy after 5 features was as follows:

Electrode(s)	LSDA(%)	FSFS(%)
Oz	70	84
Pz	83	91
Cz	80	89
Oz,Pz	86	91
Oz,Cz	83	90
Pz,Cz	83	91
Oz,Pz,Cz	86	91

The cognitive wave (as defined by the LSDA and FSFS techniques) had a latency of 575 ms for the first experiment of this subject and 496 ms. for the second experiment of this subject. Performance of the FSFS technique dropped about three percentage points from the first test whereas the performance of the LSDA technique was mixed. Classification using FSFS outperformed LSDA in all cases.

Table 22. Second subject, second experiment. Same data used to train and test. Oz electrode used.
Comments: First feature at 496 ms. picked by both electrodes. After five features, class. acc. for LSDA is 80% and for FSFS is 88%.

Table 23. Second subject, second experiment. Same data used to train and test. Pz electrode used.
Comments: First feature picked by LSDA is at 476 ms. and for FSFS at 496 ms. These are adjacent points probably identifying the same wave. After five features, class. acc. for LSDA is 79% and for FSFS is 86%.

Table 24. Second subject, second experiment. Same data used to train and test. Cz electrode used.
Comments: First feature picked by LSDA was at a latency of 476 ms. After five features, class. acc. for LSDA is 79% and for FSFS is 84%.

Table 25. Second subject, second experiment. Same data used to train and test. Oz and Pz electrodes used.
Comments: First feature picked by LSDA and FSFS had a latency of 496 ms. After five features, class. acc. for LSDA is 79% and for FSFS is 88%.

Table 26. Second subject, second experiment. Same data used to train and test. Oz and Cz electrodes used.
Comments: First feature picked by LSDA and FSFS had a latency of 496 ms. After five features, class. acc. for LSDA is 79% and for FSFS is 86%.

Table 27. Second subject, second experiment. Same data used to train and test. Pz and Cz electrodes used.
Comments: First feature picked by LSDA technique had a latency of 476 ms (Cz) whereas the one picked by FSFS had a latency of 496 ms (Pz). After five features, class. acc. for LSDA is 76% and for FSFS is 86%.

Table 28. Second subject, second experiment. Same data used to train and test. Oz, Pz and Cz electrodes used.
Comments: First feature picked by each technique had the same latency belonging to the same electrode, Oz. After five features, class. acc. for LSDA is 80% and for FSFS is 89%.

General comments on Tables 22 to 28.

Table 22. Classification accuracies obtained for subject 2, test 2 (TR1/CL1; Oz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	496	69%	70%	1	Oz	496	70%
2	Oz	436	76%	76%	2	Oz	436	76%
3	Oz	216	73%	78%	3	Oz	156	79%
4	Oz	316	75%	78%	4	Oz	316	85%
5	Oz	576	80%	75%	5	Oz	596	88%

Table 23. Classification accuracies obtained for subject 2, test 2 (TR1/CL1; Pz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	476	69%	66%	1	Pz	496	68%
2	Pz	376	76%	71%	2	Pz	576	73%
3	Pz	296	76%	71%	3	Pz	476	81%
4	Pz	216	80%	84%	4	Pz	196	81%
5	Pz	576	79%	79%	5	Pz	656	86%

Table 24. Classification accuracies obtained for subject 2, test 2 (TR1/CL1; Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Cz	476	60%	61%	1	Cz	456	64%
2	Cz	376	69%	68%	2	Cz	176	69%
3	Cz	296	79%	81%	3	Cz	336	75%
4	Cz	576	78%	79%	4	Cz	156	81%
5	Cz	216	79%	86%	5	Cz	416	86%

Table 25. Classification accuracies obtained for subject 2, test 2 (TR1/CL1; Oz,Pz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	496	69%	70%	1	Oz	496	70%
2	Oz	456	76%	76%	2	Oz	456	76%
3	Pz	296	76%	76%	3	Oz	156	79%
4	Pz	216	79%	80%	4	Oz	316	85%
5	Pz	396	79%	85%	5	Oz	596	88%

Table 26. Classification accuracies obtained for subject 2, test 2 (TR1/CL1; Oz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	496	69%	70%	1	Oz	496	70%
2	Cz	476	73%	71%	2	Oz	436	76%
3	Cz	296	75%	74%	3	Cz	336	80%
4	Oz	436	79%	76%	4	Oz	156	83%
5	Cz	376	79%	80%	5	Oz	476	86%

Table 27. Classification accuracies obtained for subject 2, test 2 (TR1/CL1; Pz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Cz	476	60%	61%	1	Pz	496	68%
2	Pz	296	73%	73%	2	Pz	576	73%
3	Cz	376	73%	73%	3	Pz	476	81%
4	Pz	576	74%	71%	4	Pz	196	81%
5	Pz	656	76%	79%	5	Pz	656	86%

Table 28. Classification accuracies obtained for subject 2, test 2 (TR1/CL1; Oz,Pz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. Accuracy LSDA	ML	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	496	69%	70%	1	Oz	496	70%
2	Oz	436	74%	76%	2	Oz	436	76%
3	Pz	376	75%	78%	3	Cz	336	80%
4	Cz	296	79%	79%	4	Pz	296	85%
5	Cz	476	80%	80%	5	Oz	356	89%

Table 29. Classification accuracies obtained for subject 1, test 1 and 2 (TR1/CL2; Oz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. Accuracy LSDA	MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	576	60%	63%	1	Oz	576	63%
2	Oz	196	59%	58%	2	Oz	796	58%
3	Oz	276	58%	55%	3	Oz	176	59%
4	Oz	476	63%	58%	4	Oz	216	59%
5	Oz	336	61%	61%	5	Oz	496	65%

Table 30. Classification accuracies obtained for subject 1, test 1 and 2 (TR1/CL2; Pz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. Accuracy LSDA	MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	576	68%	69%	1	Pz	656	56%
2	Pz	296	64%	63%	2	Pz	576	59%
3	Pz	476	74%	73%	3	Pz	276	59%
4	Pz	156	73%	78%	4	Pz	436	65%
5	Pz	376	74%	76%	5	Pz	156	64%

The amplitude of the area about 496 ms was consistently picked first by each technique. This represents an increase of about 20 ms in latency from the first experiment. This is probably not a significant difference. As previously stated, this is probably the location of the "cognitive" wave. Classification accuracy after 5 features was as follows:

Electrode(s)	LSDA(%)	FSFS(%)
Oz	80	88
Pz	79	86
Cz	79	86
Oz,Pz	79	88
Oz,Cz	79	86
Pz,Cz	76	86
Oz,Pz,Cz	80	89

Table 29. First subject, first and second experiment. Data from first experiment used to train, data from second experiment used to test. Oz electrode used.
Comments: Overall accuracy when using different samples to train and to test is considerably lower than before. A possible explanation may be as follows: For the first experiment (electrode Oz) features picked by the FSFS classifier were located at 176, 196, 216, 496 and 576 ms respectively. For the second test they were located at 156, 336, 496, 536 and 596 ms respectively. First features picked were located at 576 and 496 ms respectively. It is therefore not surprising that when the features from the first set of tests were used to classify the second set of tests a substantially lower classification rate was obtained.

If the location of the first feature picked is indicative of the location of the cognitive wave P300 then one can see that the location of P300 has changed from the first to the second test. Only one feature was picked both times, the one located at 496 ms. It appears as if the character and perhaps the complexity of the waveform have changed over the period of time between the two tests. This may be due to subject habituation, or perhaps a lack of an adequate experimental paradigm. Another possible explanation may be found in the way that FSFS picks features. During any step in the procedure several features may be found any one of which may yield the same classification accuracy. For example, in Table 1, third step, three features were found that woulds yield the same class. acc. and these features were located at 176, 216 and 256 ms respectively. When faced with more than one feature that yields the same accuracy, and with no added information, the program, in a very arbitrary manner, picks the feature with the fastest latency. So in the example just given, it picked the feature at 176 ms. At the next step, nine features were found that would yield the same accuracy. Again the process was repeated. So only one of a possibly very large number of trees was followed; i.e., the feature at 176 ms. Obviously, this is not an exhaustive search and undoubtedly leads to a suboptimal set of features.

After five features, class. acc. for LSDA is 61% and for FSFS is 65%.
Table 30. First subject, first and second experiment. Data from first experiment used to train, data from second experiment used to test. Pz electrode used.
Comments:

As with electrode Oz, class. acc. of FSFS is low. After five features, it is only 64%. The results obtained with the LSDA technique and with LSDA features picked FSFS class. technique (blocks 9, 10 and 11) are also equally lower. For the first time, classification accuracy using LSDA surpasses accuracy obtained by FSFS. It is also interesting to note that the accuracy obtained in column 5 is now greater than the conventional LSDA accuracy. Numbers given in column 5 are the accuracy obtained using features picked by the LSDA technique (given in column 3).

It is difficult to explain the nature of the above changes. One may surmise that an explanation may lie in the inherent differences between the two techniques. The LSDA simply weights the amplitudes at certain latencies and linearly combines them. The FSFS depends on the covariance of the samples at the different latencies. The fact that the accuracy obtained in column 5 is larger than the accuracy obtained in column 4 still points towards the superiority of FSFS as a classification technique.

After five features class. acc. for LSDA was 75% (also achieved after 3 features) and for FSFS it was 64% (after 4 features it achieved 65%).

Table 31. First subject, first and second experiment. Data from first experiment used to train, data from second experiment used to test. Cz electrode used.

Comments: Comments made in the discussion of the preceeding table also apply here. Maximum classification accuracy: LSDA, 69% after 3 features and FSFS, 63% after 5 features.

Table 32. First subject, first and second experiment. Data from first experiment used to train, data from second experiment used to test. Oz and Pz electrodes used.

Comments:

An additional type of test was done with this data. The results given in the last three tables were computed as follows (for the FSFS technique): the features and the corresponding covariance matrix needed by the quadratic classifier were computed from the first test and then each data vector from the second test classified. An alternate way would be to select the features from the first test but to compute the covariance matrix from the second test. The re-definition of the covariance matrix improved the classification accuracy by approximately 10%.

Maximum classification accuracy: LSDA: 73% after 4 features; FSFS: 63% after 1 feature; FSFS with re-defined covariance matrix: 74% after 4 features.

Table 33. First subject, first and second experiment. Data from first experiment used to train, data from second experiment used to test. Oz and Cz electrodes used.

Comments: Overall accuracy was low for both LSDA and FSFS. Maximum classification accuracy: LSDA: 66% after 5 features; FSFS: 63% after 1 feature; FSFS with re-defined covariance matrix: 60% after 5 features.

Table 34. First subject, first and second experiment. Data from first experiment used to train, data from second experiment used to test. Pz and Cz electrodes used.

Comments: Redefining the covariance matrix had the effect of increasing overall classification accuracy to almost 80%. Maximum classification accuracy: LSDA: 69% after 3 features; FSFS: 66% after 4 features; FSFS with redefined covariance matrix: 79% after 5 features.

Table 35. First subject, first and second experiment. Data from first ex-

Table 31. Classification accuracies obtained for subject 1, test 1 and 2 (TR1/CL2; Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Cz	576	56%	53%	1	Cz	296	54%
2	Cz	296	65%	63%	2	Cz	556	61%
3	Cz	476	68%	69%	3	Cz	156	61%
4	Cz	376	68%	68%	4	Cz	396	61%
5	Cz	656	66%	70%	5	Cz	276	63%

Table 32. Classification accuracies obtained for subject 1, test 1 and 2 (TR1/CL2; Oz,Pz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	576	68%	69%	1	Oz	576	63%
2	Oz	196	63%	65%	2	Oz	196	58%
3	Pz	476	71%	73%	3	Pz	656	58%
4	Pz	296	73%	73%	4	Oz	216	60%
5	Pz	216	71%	73%	5	Pz	296	54%

Table 33. Classification accuracies obtained for subject 1, test 1 and 2 (TR1/CL2; Oz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Cz	576	59%	60%	1	Oz	576	63%
2	Oz	196	61%	64%	2	Oz	196	58%
3	Cz	296	55%	61%	3	Cz	276	53%
4	Cz	476	65%	65%	4	Cz	596	58%
5	Cz	196	66%	68%	5	Oz	256	60%

periment used to train, data from second experiment used to test. Oz, Pz and Cz electrodes used.
Comments: Maximum classification accuracy: LSDA: 74% after 5 features; FSFS: 60% after 4 features; FSFS with redefined covariance matrix: 74% after 5 features.
General comments on Tables 29 to 35.

Classification accuracy has been reduced by utilizing features and results from one test to train a classifier used to classify samples from a different test. It appears as if LSDA is more impervious to changes of this type than FSFS. This may be corrected, however, by a more extensive study of the feature selection process of the FSFS technique. This is evidenced by the results given in column or block 11. Redefining the covariance matrix improved the classification accuracy by as much as 10%.

Maximum Classification Accuracy:

Electrode(s)	LSDA(%-# of features)	FSFS(%-# of features)	FSFS-redefine cov. matrix (%-# of features)
Oz	63(4)	65(5)	
Pz	74(3)	65(4)	
Cz	68(3)	63(5)	
Oz,Pz	73(4)	63(1)	74(5)
Oz,Cz	66(5)	63(1)	60(5)
Pz,Cz	69(3)	66(4)	79(5)
Oz,Pz,Cz	74(5)	63(1)	74(5)

Table 36. Second subject, first and second experiment. Data from first experiment used to train, data from second experiment used to test. Oz electrode used.
Comments: Most of the comments made during the analysis of tables 29 to 35 also apply here. General class. acc. has been lowered by using different data to train and test. Maximum classification accuracy: LSDA: 66% after 2 features; FSFS: 69% after 2 features.
Table 37. Second subject, first and second experiment. Data from first experiment used to train, data from second experiment used to test. Pz electrode used.
Comments: Maximum classification accuracy: LSDA: 66% after 5 features; FSFS: 71% after 5 features.
Table 38. Second subject, first and second experiment. Data from first experiment used to train, data from second experiment used to test. Cz electrode used.
Comments: Maximum classification accuracy: LSDA: 68% after 3 features; FSFS: 73% after 4 features.
Table 39. Second subject, first and second experiment. Data from first experiment used to train, data from second experiment used to test. Oz and Pz electrodes used.
Comments: Maximum classification accuracy: LSDA: 66% after 2 features; FSFS: 66% after 4 features.
Table 40. Second subject, first and second experiment. Data from first experiment used to train, data from second experiment used to test. Oz and Cz electrodes used.
Comments: Maximum classification accuracy: LSDA: 64% after 1 feature; FSFS: 66% after 2 features.

Table 34. Classification accuracies obtained for subject 1, test 1 and 2(TR1/CL2;Pz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	576	68%	69%	1	Pz	656	56%
2	Cz	296	60%	60%	2	Pz	576	59%
3	Cz	476	69%	70%	3	Cz	276	65%
4	Pz	176	69%	71%	4	Cz	416	66%
5	Cz	176	69%	70%	5	Pz	176	66%

Table 35. Classification accuracies obtained for subject 1, test 1 and 2(TR1/CL2;Oz,Pz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	576	68%	69%	1	Oz	576	63%
2	Oz	196	65%	65%	2	Oz	196	58%
3	Cz	296	59%	61%	3	Pz	656	58%
4	Cz	196	58%	63%	4	Oz	216	60%
5	Pz	476	74%	73%	5	Pz	296	54%

Table 36. Classification accuracies obtained for subject 2, test 1 and 2(TR1/CL2;Oz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	476	64%	64%	1	Oz	476	64%
2	Oz	196	66%	68%	2	Oz	136	69%
3	Oz	136	64%	65%	3	Oz	596	68%
4	Oz	236	63%	64%	4	Oz	616	61%
5	Oz	216	60%	59%	5	Oz	256	56%

Table 37. Classification accuracies obtained for subject 2, test 1 and 2(TR1/CL2;Pz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	476	63%	64%	1	Pz	476	63%
2	Pz	516	56%	59%	2	Pz	136	68%
3	Pz	276	58%	58%	3	Pz	376	64%
4	Pz	196	64%	61%	4	Pz	256	66%
5	Pz	136	66%	68%	5	Pz	156	71%

Table 38. Classification accuracies obtained for subject 2, test 1 and 2(TR1/CL2;Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Cz	476	60%	61%	1	Cz	516	65%
2	Cz	196	58%	59%	2	Cz	256	61%
3	Cz	256	68%	64%	3	Cz	176	65%
4	Cz	576	68%	65%	4	Cz	376	73%
5	Cz	136	65%	64%	5	Cz	596	64%

Table 39. Classification accuracies obtained for subject 2, test 1 and 2(TR1/CL2;Oz,Pz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	476	64%	64%	1	Pz	476	63%
2	Oz	196	66%	64%	2	Oz	536	63%
3	Pz	256	59%	61%	3	Oz	216	65%
4	Oz	156	65%	61%	4	Pz	316	66%
5	Pz	476	61%	60%	5	Oz	316	64%

Table 41. Second subject, first and second experiment. Data from first experiment used to train, data from second experiment used to test. Pz and Cz electrodes used.
Comments: Maximum classification accuracy: LSDA: 63% after 1 feature; FSFS: 66% after 5 features.
Table 42. Second subject, first and second experiment. Data from first experiment used to train, data from second experiment used to test. Oz, Pz and Cz electrodes used.
Comments: Maximum classification accuracy: LSDA: 66% after 2 features; FSFS: 66% after 3 features.
General comments on Tables 36 to 42.

General comments made for the preceeding set of tables also apply here. Overall accuracy has been lowered, performance of LSDA and FSFS are about equal. Maximum classification accuracy:

Electrode(s)	LSDA(%-# of features)	FSFS(%-# of features)
Oz	66(2)	69(2)
Pz	66(5)	71(5)
Cz	65(4)	73(4)
Oz,Pz	66(2)	66(4)
Oz,Cz	66(2)	66(2)
Pz,Cz	63(1)	66(5)
Oz,Pz,Cz	66(2)	66(3)

In the following series of tests, data from the first subject was used to train the classifiers and data from the second subject was used to test the classifiers.
Table 43. First and second subject, first experiment. Data from first subject used to train, data from second subject used to test. Oz electrode used.
Comments: In a quasi-anticipated result, overall classification accuracy has decreased. Maximum classification accuracy: LSDA: 63% after 4 features; FSFS: 68% after 4 features.
Table 44. First and second subject, first experiment. Data from first subject used to train, data from second subject used to test. Pz electrode used.
Comments: Maximum classification accuracy: LSDA: 73% after 2 features; FSFS: 65% after 2 features.
Table 45. First and second subject, first experiment. Data from first subject used to train, data from second subject used to test. Cz electrode used.
Comments: Maximum classification accuracy: LSDA: 68% after 2 features; FSFS: 65% after 2 features.
Table 46. First and second subject, first experiment. Data from first subject used to train, data from second subject used to test. Oz and Pz electrodes used.
Comments: Maximum classification accuracy: LSDA: 70% after 5 features; FSFS: 71% after 1 feature.
Table 47. First and second subject, first experiment. Data from first subject used to train, data from second subject used to test. Oz and Cz electrodes used.
Comments: Maximum classification accuracy: LSDA: 68% after 3 features; FSFS:

Table 40. Classification accuracies obtained for subject 2, test 1 and 2(TR1/CL2;Oz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	476	64%	64%	1	Oz	476	64%
2	Oz	196	66%	68%	2	Cz	576	66%
3	Cz	256	63%	64%	3	Oz	176	61%
4	Cz	376	64%	64%	4	Oz	136	64%
5	Cz	136	63%	65%	5	Oz	236	58%

Table 41. Classification accuracies obtained for subject 2, test 1 and 2(TR1/CL2;Pz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	476	63%	64%	1	Pz	476	63%
2	Pz	196	57%	59%	2	Cz	216	65%
3	Cz	436	55%	58%	3	Pz	336	60%
4	Cz	276	57%	56%	4	Pz	216	63%
5	Cz	376	61%	63%	5	Pz	156	66%

Table 42. Classification accuracies obtained for subject 2, test 1 and 2(TR1/CL2;Oz,Pz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	476	64%	64%	1	Pz	476	63%
2	Oz	196	66%	68%	2	Oz	536	63%
3	Cz	256	63%	64%	3	Cz	376	66%
4	Cz	376	64%	65%	4	Oz	196	65%
5	Pz	476	66%	68%	5	Cz	516	66%

Table 43. Classification accuracies obtained for subject 1 and 2, test 1(TR1/CL1;Oz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	576	59%	64%	1	Oz	576	64%
2	Oz	196	61%	63%	2	Oz	196	63%
3	Oz	276	60%	59%	3	Oz	176	60%
4	Oz	476	63%	58%	4	Oz	216	68%
5	Oz	336	61%	59%	5	Oz	496	63%

Table 44. Classification accuracies obtained for subject 1 and 2, test 1(TR1/CL1;Pz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	576	68%	71%	1	Pz	656	74%
2	Pz	296	73%	74%	2	Pz	576	75%
3	Pz	476	71%	70%	3	Pz	276	71%
4	Pz	156	69%	65%	4	Pz	436	65%
5	Pz	376	70%	69%	5	Pz	156	68%

Table 45. Classification accuracies obtained for subject 1 and 2, test 1(TR1/CL1;Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Cz	576	64%	65%	1	Cz	296	60%
2	Cz	296	68%	59%	2	Cz	556	65%
3	Cz	476	61%	54%	3	Cz	156	64%
4	Cz	376	59%	61%	4	Cz	396	61%
5	Cz	656	68%	68%	5	Cz	276	59%

Table 46. Classification accuracies obtained for subject 1 and 2, test 1(TR1/CL1;Oz,Pz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. Accuracy LSDA	MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	576	68%	71%	1	Oz	576	71%
2	Oz	196	69%	64%	2	Oz	196	63%
3	Pz	476	61%	60%	3	Pz	656	59%
4	Pz	296	63%	65%	4	Oz	216	70%
5	Pz	216	70%	71%	5	Pz	296	69%

Table 47. Classification accuracies obtained for subject 1 and 2, test 1(TR1/CL1;Oz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. Accuracy LSDA	MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Cz	576	64%	65%	1	Oz	576	64%
2	Oz	196	65%	61%	2	Oz	196	63%
3	Cz	296	68%	68%	3	Cz	276	60%
4	Cz	476	61%	64%	4	Cz	596	59%
5	Cz	196	63%	59%	5	Oz	256	64%

Table 48. Classification accuracies obtained for subject 1 and 2, test 1(TR1/CL1;Pz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. Accuracy LSDA	MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	576	68%	71%	1	Pz	656	74%
2	Cz	296	65%	61%	2	Pz	576	71%
3	Cz	476	68%	68%	3	Cz	276	74%
4	Pz	176	65%	68%	4	Cz	416	68%
5	Cz	176	61%	59%	5	Pz	176	64%

64% after 1 feature.

Table 48. First and second subject, first experiment. Data from first subject used to train, data from second subject used to test. Pz and Cz electrodes used.

Comments: Maximum classification accuracy: LSDA: 68% after 1 feature; FSFS: 74% after 1 feature.

Table 49. First and second subject, first experiment. Data from first subject used to train, data from second subject used to test. Oz, Pz and Cz electrodes used.

Comments: Maximum classification accuracy: LSDA: 68% after 1 feature; FSFS: 69% after 3 features.

General comments on Tables 43 to 49.

The results just described represent an attempt at classifying the data for one subject, using results from another subject. On the average, the classification accuracy was poor (about 70%) with neither technique having an apparent advantage over the other. Maximum classification accuracy:

Electrode(s)	LSDA(%-# of features)	FSFS(%-# of features)
Oz	63(4)	68(4)
Pz	73(2)	75(2)
Cz	68(2)	65(2)
Oz,Pz	70(5)	71(1)
Oz,Cz	68(3)	64(1)
Pz,Cz	68(1)	74(1)
Oz,Pz,Cz	68(1)	69(3)

In the following series of tests, data from the second subject, second experiment was used to train the classifiers and data from the first subject, second experiment used to train the classifiers.

Table 50. First and second subject, second experiment. Data from second subject used to train, data from first subject used to test. Oz electrode used.

Comments: General accuracy of this series of tests is low. Practically no difference between this series of tests and the results given in Tables 43 to 49 was found. Overall class. acc. was found to be about 65 - 70%. Maximum classification accuracy: LSDA: 64% after 1 feature; FSFS: 68% after 1 feature.

Table 51. First and second subject, second experiment. Data from second subject used to train, data from first subject used to test. Pz electrode used.

Comments: Maximum classification accuracy: LSDA: 76% after 2 features; FSFS: 76% after 1 feature.

Table 52. First and second subject, second experiment. Data from second subject used to train, data from first subject used to test. Cz electrode used.

Comments: Maximum classification accuracy: LSDA: 71% after 2 features; FSFS: 73% after 1 feature.

Table 53. First and second subject, second experiment. Data from second subject used to train, data from first subject used to test. Oz and Pz electrodes used.

Comments: Maximum classification accuracy: LSDA: 65% after 1 feature; FSFS: 68% after 1 feature.

Table 54. First and second subject, second experiment. Data from second subject used to train, data from first subject used to test. Oz and Cz

Table 49. Classification accuracies obtained for subject 1 and 2, test 1(TR1/CL1;Oz,Pz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	576	68%	71%	1	Oz	576	64%
2	Oz	196	63%	64%	2	Oz	196	63%
3	Cz	296	68%	69%	3	Pz	656	69%
4	Cz	196	61%	59%	4	Oz	216	68%
5	Pz	476	64%	61%	5	Pz	296	65%

Table 50. Classification accuracies obtained for subject 1 and 2, test 2(TR2/CL2;Oz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	496	64%	68%	1	Oz	496	68%
2	Oz	436	62%	63%	2	Oz	436	63%
3	Oz	216	60%	64%	3	Oz	156	68%
4	Oz	296	58%	54%	4	Oz	316	63%
5	Oz	576	58%	51%	5	Oz	596	61%

Table 51. Classification accuracies obtained for subject 1 and 2, test 2(TR2/CL2;Pz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Pz	476	70%	69%	1	Pz	496	76%
2	Pz	376	76%	76%	2	Pz	576	73%
3	Pz	296	71%	73%	3	Pz	476	70%
4	Pz	216	68%	64%	4	Pz	196	64%
5	Pz	576	71%	68%	5	Pz	656	66%

Table 52. Classification accuracies obtained for subject 1 and 2, test 2(TR2/CL2;Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Cz	476	70%	73%	1	Cz	456	73%
2	Cz	376	71%	79%	2	Cz	176	63%
3	Cz	296	64%	66%	3	Cz	336	64%
4	Cz	576	61%	69%	4	Cz	156	63%
5	Cz	216	64%	71%	5	Cz	416	60%

Table 53. Classification accuracies obtained for subject 1 and 2, test 2(TR2/CL2;Oz,Pz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	496	65%	68%	1	Oz	496	68%
2	Oz	436	63%	63%	2	Oz	456	63%
3	Pz	296	55%	55%	3	Oz	156	68%
4	Pz	216	64%	54%	4	Oz	316	63%
5	Pz	396	59%	55%	5	Oz	596	62%

Table 54. Classification accuracies obtained for subject 1 and 2, test 2(TR2/CL2;Oz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	496	65%	68%	1	Oz	496	68%
2	Cz	476	74%	75%	2	Oz	436	63%
3	Cz	296	69%	68%	3	Cz	336	54%
4	Oz	436	63%	64%	4	Oz	156	61%
5	Cz	376	70%	66%	5	Oz	476	60%

electrodes used.
Comments: Maximum classification accuracy: LSDA: 74% after 2 features; FSFS: 68% after 1 feature.
Table 55. First and second subject, second experiment. Data from second subject used to train, data from first subject used to test. Oz, Pz and Cz electrodes used.
Comments: Maximum classification accuracy: LSDA: 70% after 1 feature; FSFS: 76% after 1 feature.
Table 56. First and second subject, second experiment. Data from second subject used to train, data from first subject used to test. Oz, Pz and Cz electrodes used.
Comments: Maximum classification accuracy: LSDA: 74% after 2 features; FSFS: 68% after 1 feature.
General comments on Tables 50 to 56.

An interesting result from this series of tests is that with only one feature from electrode Pz, the FSFS technique was able to correctly classify over 76% of the responses. This feature was located at a latency of 496 ms.

Maximum classification accuracy:

Electrode(s)	LSDA(%-# of features)	FSFS(%-# of features)
Oz	64(1)	68(1)
Pz	76(2)	76(1)
Cz	71(2)	73(1)
Oz,Pz	65(1)	68(1)
Oz,Cz	74(2)	68(1)
Pz,Cz	70(1)	76(1)
Oz,Pz,Cz	74(2)	68(1)

CONCLUSIONS

The general conclusions for the above sets of tests will be divided into two groups. The first group will be formed by those results obtained when the same data set was used to train and to test the two classifiers. The second group will be formed by those results obtained when different data sets were used to train and test the classifiers.

Conclusions for first group of tests.

It appears that both classifiers consistently picked the "cognitive wave" as the first feature. This indicates that this is probably the region of maximal separability between the expected and the unexpected event. The results of two tests for the first subject indicate that the latency of this wave decreased from 575 ms to 496 ms between the first and second tests. This may be due to expectation on part of the subject. The second subject, however, showed a slightly different result. For the first experiment, the first feature picked had a latency of 475 ms. Whereas for the second experiment it had a latency of 496 ms.

For the first subject, classification accuracy using the quadratic classifier was as high as 94% utilizing 2 electrodes and five features. For the LSDA technique it was 90% using 5 features and 2 electrodes. The quadratic classification technique outperformed the LSDA technique is every instance; this difference in performance was as high as 14% and as low as 4%.

Table 55. Classification accuracies obtained for subject 1 and 2, test 2(TR2/CL2;Pz,Cz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Cz	476	70%	73%	1	Pz	496	76%
2	Pz	296	65%	70%	2	Pz	576	73%
3	Cz	376	68%	68%	3	Pz	476	70%
4	Pz	576	64%	70%	4	Pz	196	64%
5	Pz	656	69%	75%	5	Pz	656	66%

Table 56. Classification accuracies obtained for subject 1 and 2, test 2(TR2/CL2;Oz,Cz,Pz)

LSDA					FSFS			
Feature No.	Site	Latency ms	Class. LSDA	Accuracy MS	Feature No.	Site	Latency ms	Class. Acc.-%
1	Oz	496	65%	68%	1	Oz	496	68%
2	Cz	476	74%	75%	2	Oz	436	63%
3	Cz	296	69%	68%	3	Cz	336	54%
4	Oz	436	66%	64%	4	Pz	296	55%
5	Pz	376	71%	73%	5	Oz	356	64%

For the second subject, classification accuracy using the quadratic classifier was as high as 93% using 5 features and 3 electrodes. For the LSDA technique it was 92% using 5 features and 3 electrodes. As with the first subject the quadratic classification technique outperformed or was equal to LSDA technique in every instance; this difference in performance was as high as 18% and as low as 0%.

Features picked by the classifiers for the first experiment were different than those picked for the second experiment. This change, probably due to habituation, undoubtedly affected the classification accuracy of the classifiers when data from different experiments was used to train and test.

Conclusions for second group of tests.

Overall performance of both classifiers deteriorated when data from one experiment was used to train and data from another experiment used to test the classifiers. This result is the same whether the same subject (across time) or different subjects were used. Classification accuracy drops an average of 15-20% for both classifiers, although the LSDA technique shows slightly better results than FSFS. As mentioned earlier, this may be due to the probably sub-optimal feature selection technique used by FSFS.

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